Continuing Education Course

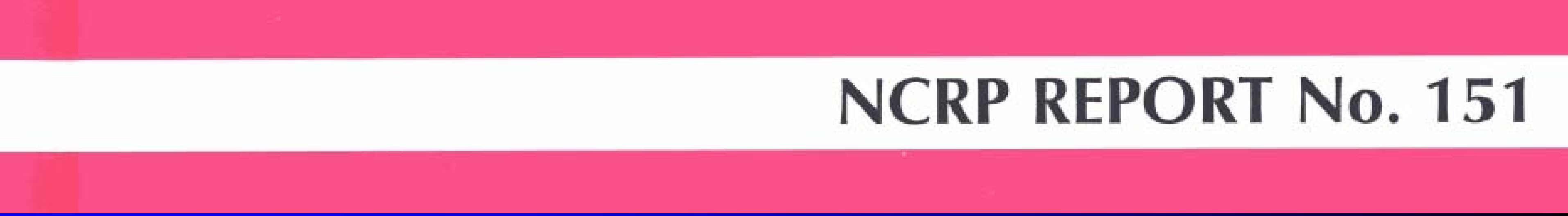
WE-B-224A-01

SHIELDING III :

PRACTICAL EXAMPLES, INCLUDING IMRT, TBI, SRS

JAMES E. RODGERS

AAPM 2006



NCRP REPORT No. 151

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

NCRP, Bethesda, MD (December 2005)

NCRP REPORT No. 151

This Report was prepared through a joint effort of
NCRP Scientific Committee 46-13
and
AAPM Task Group 57.

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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.

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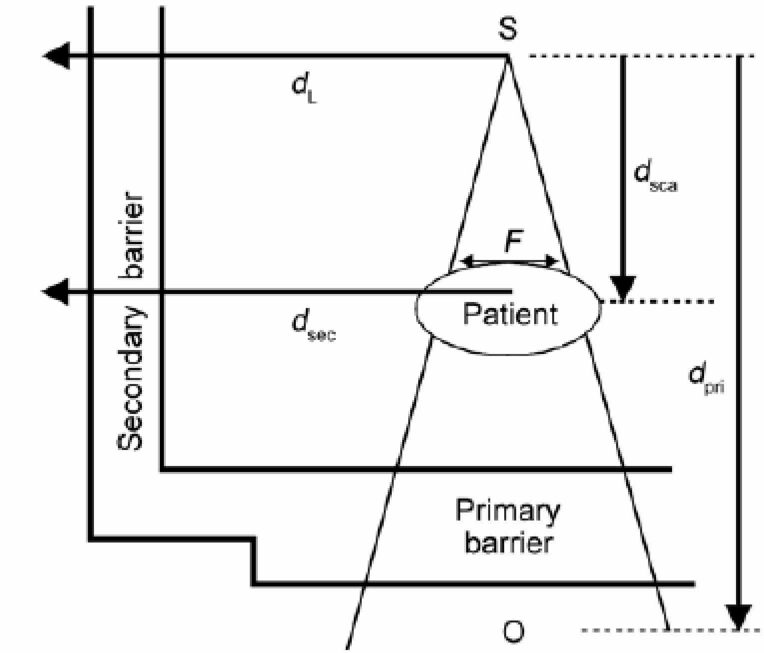
$$B_L = \frac{P\, d_L^2}{10^{-3}\, W\, T}$$

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



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

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

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

And for n > 1 the barrier thickness (t_{barrier}) is given by:

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

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.

$$WU]_{\mathrm{pri}} = WU]_{\mathrm{wall\ scat}} \tag{3.4}$$

$$= (W_{\mathrm{conv}}\ U_{\mathrm{conv}} + W_{\mathrm{TBI}}\ U_{\mathrm{TBI}} + W_{\mathrm{IMRT}}\ U_{\mathrm{IMRT}} + W_{\mathrm{QA}}\ U_{\mathrm{QA}} + \ldots)$$

$$W_{\mathrm{L}} = W_{\mathrm{conv}} + W_{\mathrm{TBI}} + C_{\mathrm{I}}\ W_{\mathrm{IMRT}} + C_{\mathrm{QA}}\ W_{\mathrm{QA}} + \ldots$$

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)

$$C_{\mathrm{I}} = \frac{MU_{\mathrm{IMRT}}}{MU_{\mathrm{conv}}}$$

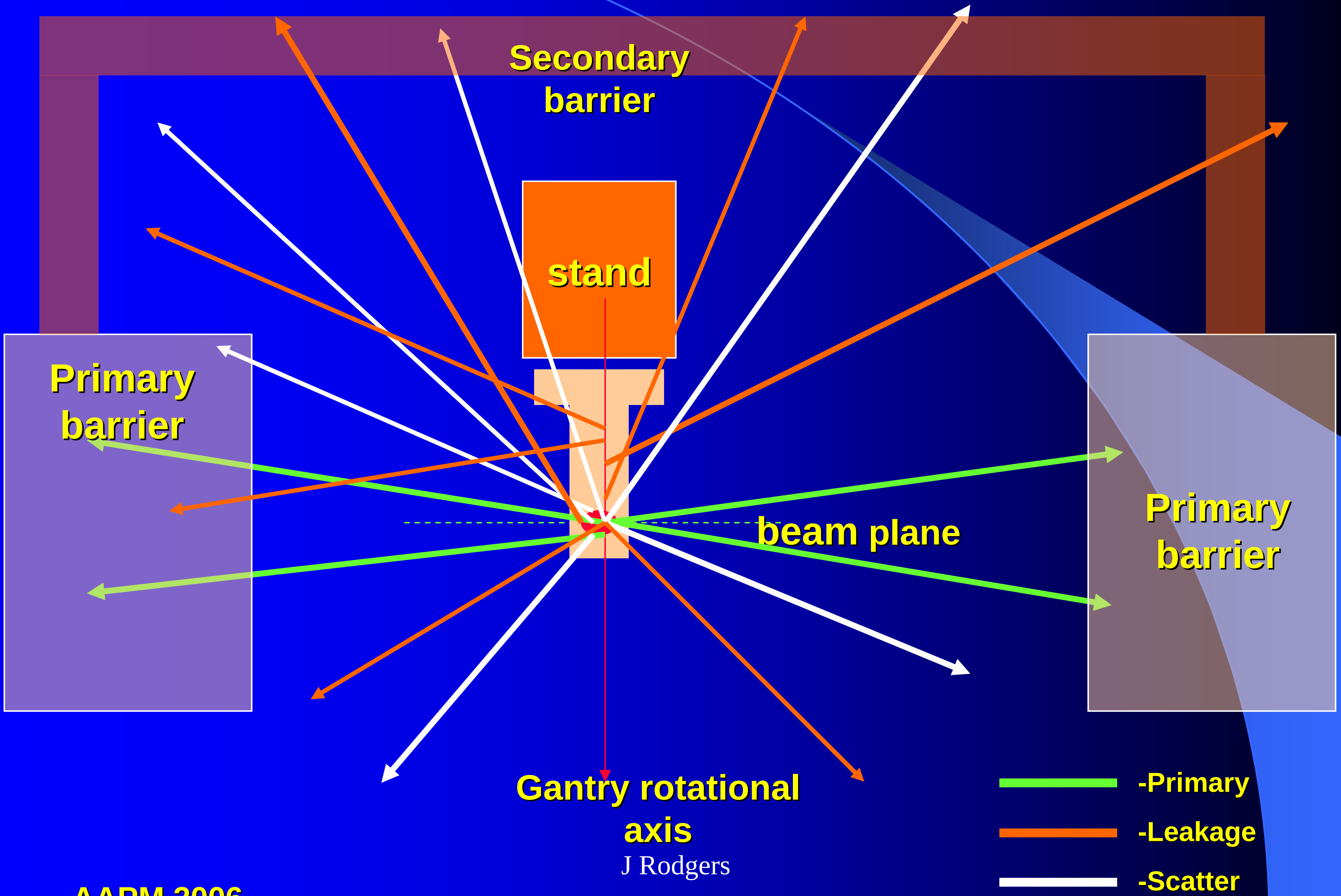
[~ 2 - 10]

$$MU_{\mathrm{IMRT}} = \Sigma_{\mathrm{i}} \frac{MU_{\mathrm{i}}}{(D_{\mathrm{pre}})_{\mathrm{i}}}$$

EXAMPLES

- 6 MV Vault--Primary and Secondary Barriers
- Low Energy Maze Entrance/Door
- High Energy Maze Door
- TBI Considerations
- Robotic SRS Machine

Medical Linear Accelerator (6-25 MV X-rays)



Secondary barrier

stand

Primary barrier

Primary barrier

beam plane

Gantry rotational axis

-Primary

-Leakage

-Scatter

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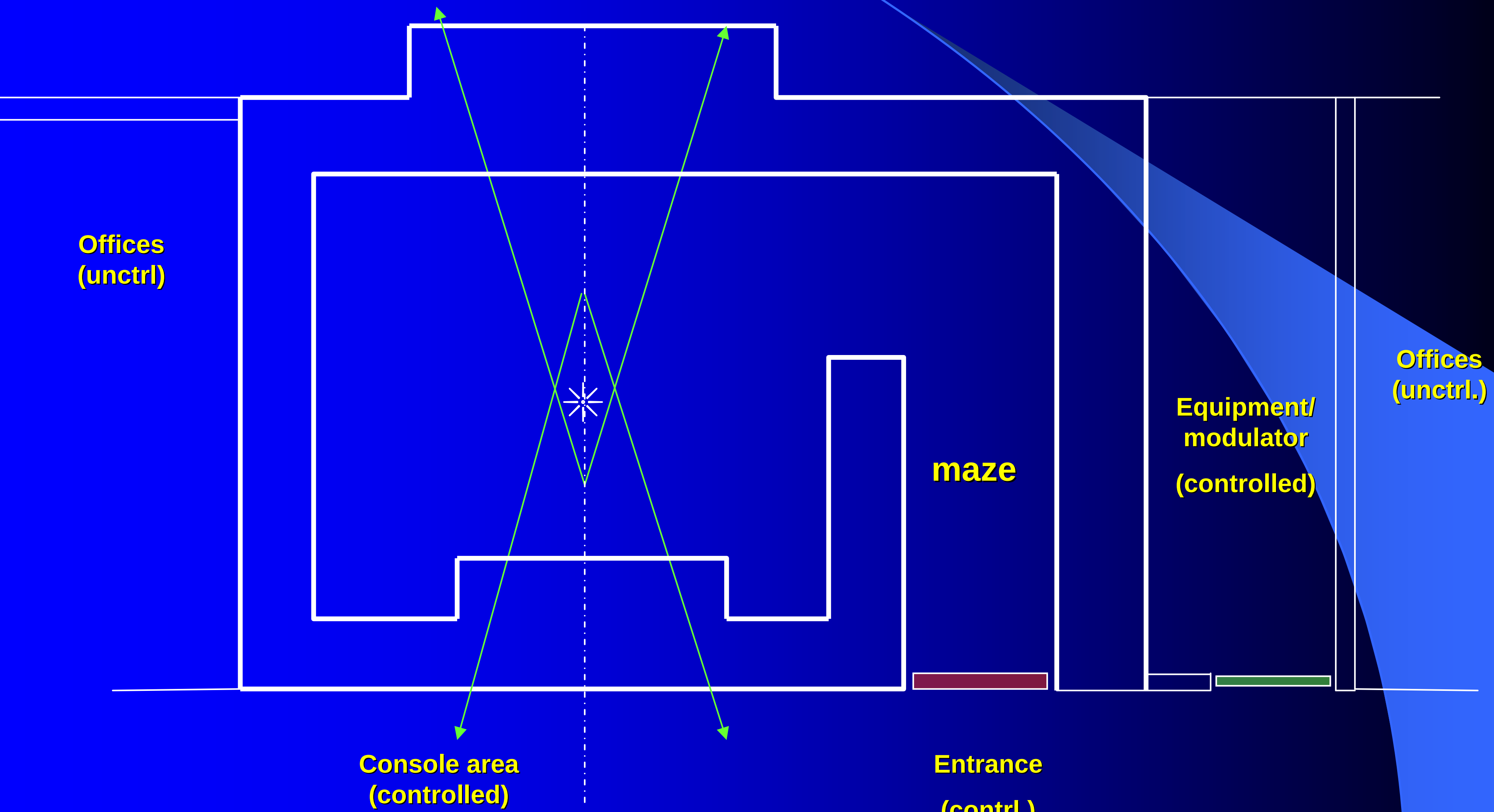
Example: 6 MV Therapy Vault



Parking lot (uncontrolled, unattended)

Offices (unctrl)

maze

Equipment/ modulator

(controlled)

Offices (unctrl.)

Console area (controlled)

Entrance

(contrl.)

Primary Barrier Workload

W_{pri} = workload per wk at 1 m (e.g., Gy*m^2/wk) (for primary barriers)

For this example,

$$W_{pri} = 35 \text{ pt/day} * 5 \text{ day/wk} * 2.5 \text{ Gy/pt} * (1/0.6)$$

$$= 35 * 5 \text{ pt/wk} * 4.17 \text{ Gy/pt}$$

$$= 730 \text{ Gy/wk} = 73.0 \times 10^3 \text{ cGy/wk}$$

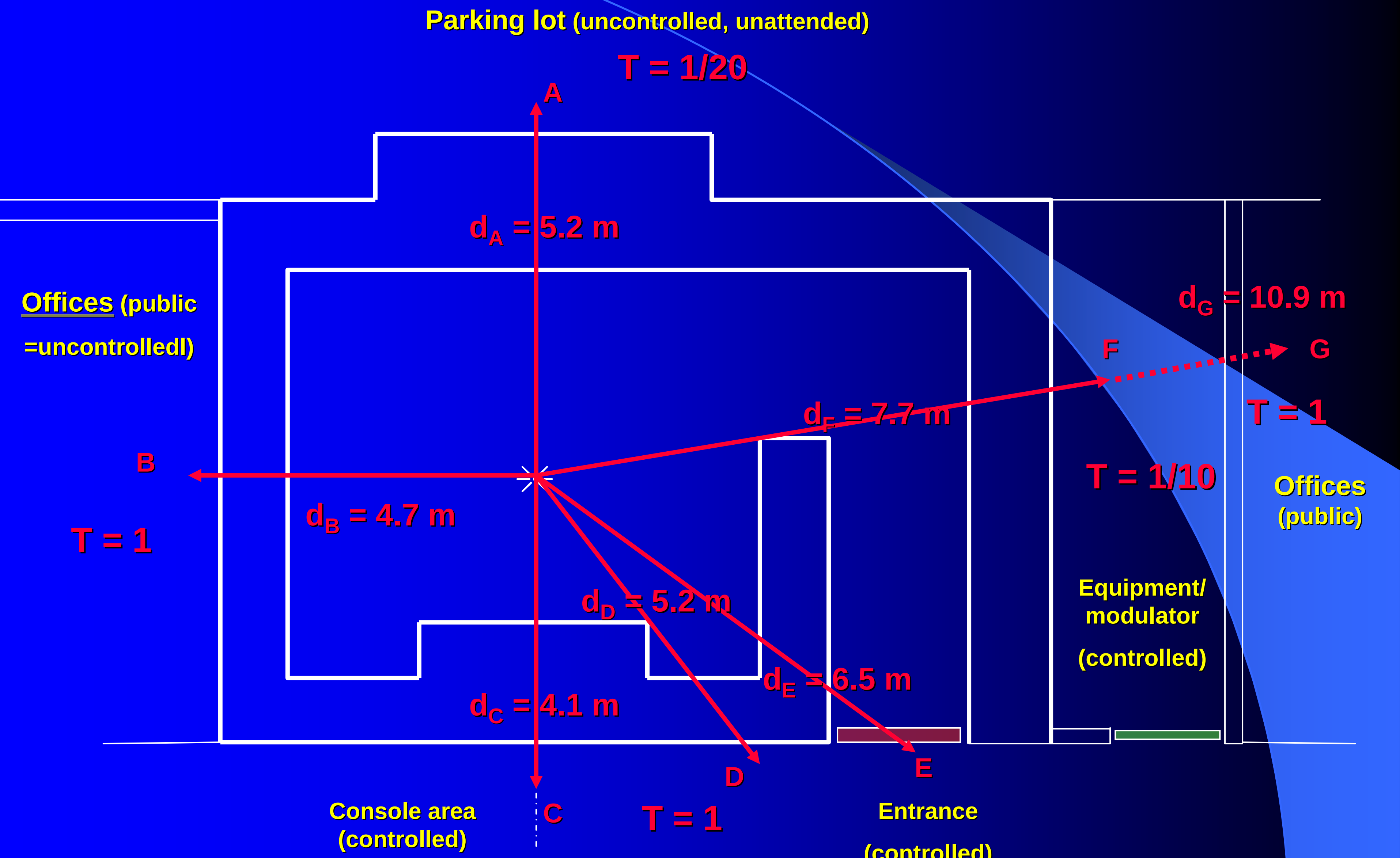
Here the 0.6 factor accounts for patient attenuation.

…Primary Barriers

Suggested primary beam TVLs [NCRP 151,Table B.2]

MV	Barrier material	TVL_1 (cm)	TVL_{eq} (cm)
6	Concrete	37	33
	Steel	10.	10.
	Lead(Pb)	5.7	5.7
18	Concrete	45	43
	Steel	11.	11.
	Lead(Pb)	5.7	5.7

Example: 6 MV Therapy Vault



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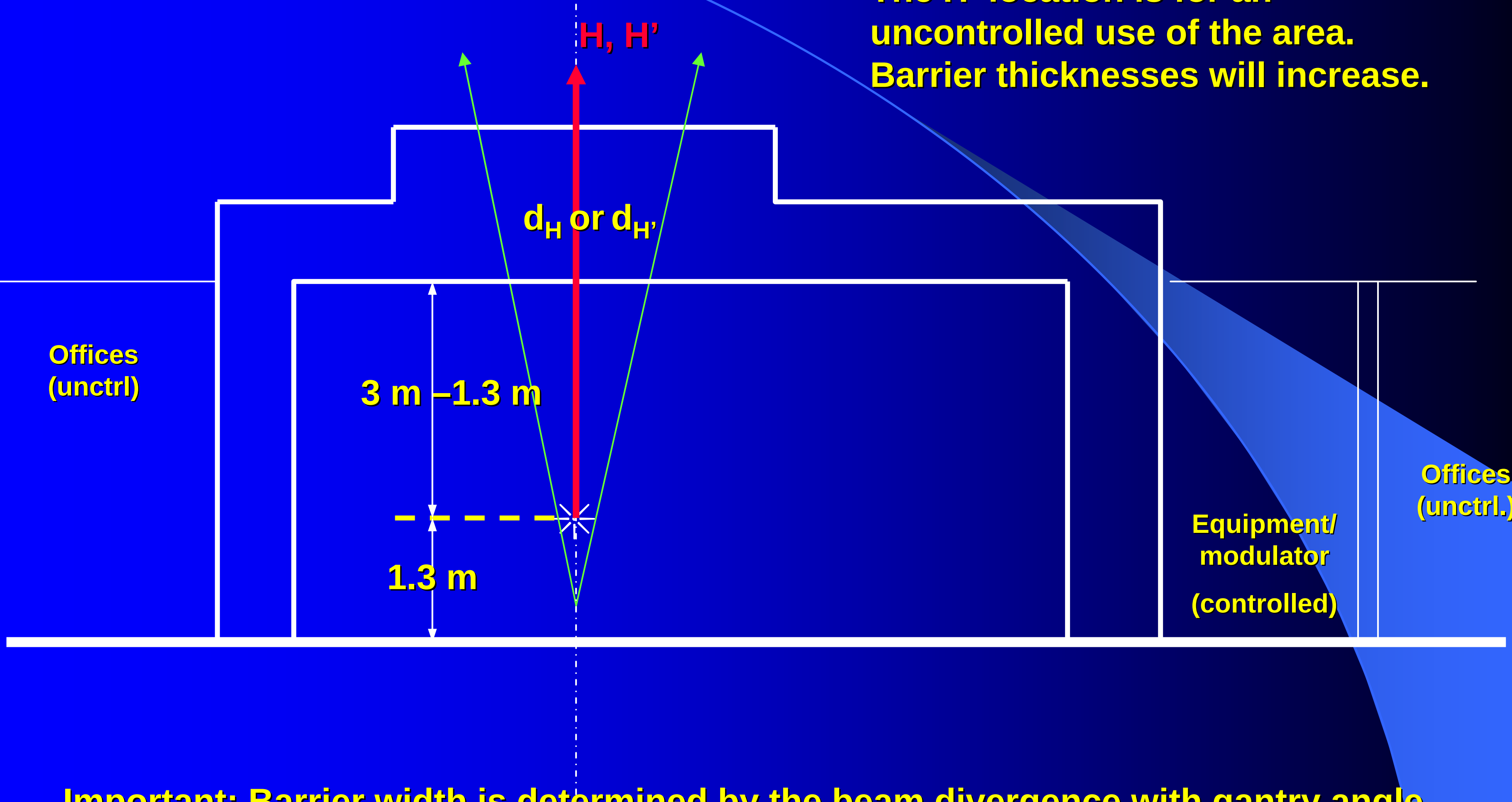
Example: 6 MV Therapy Vault---Up on the roof.

The H’ location is for an uncontrolled use of the area. Barrier thicknesses will increase.

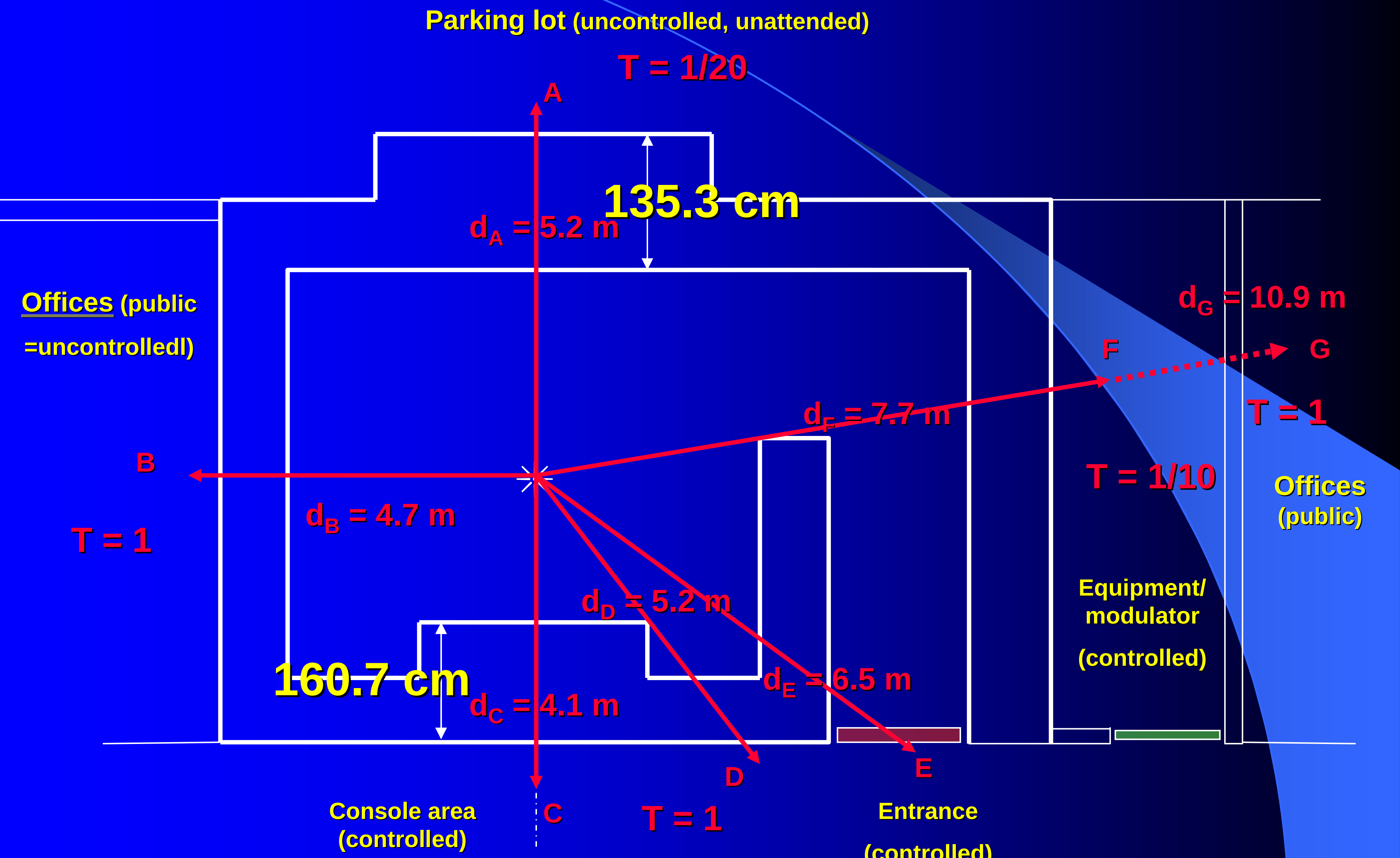


Important: Barrier width is determined by the beam divergence with gantry angle. Usually the width will match the primary barrier at the wall(s).

Primary Walls

location	type	P (mSv/wk)	U	T	d_s (m)	B_{pri}	n	x (cm)
A	Unctrl.	0.02	0.2	0.05	5.2+1	1.05e-4	3.98	135.3
C	Ctrl.	0.1	0.2	1	4.1+1	1.77e-5	4.75	160.7
H	Ctrl.	0.1	0.3	0.1	3.8+1	1.05e-4	3.98	135.3
H’	Unctrl.	0.02	0.3	1	4.1+1	2.36e-6	5.62	189.6

Example: 6 MV Therapy Vault



Parking lot (uncontrolled, unattended)

T = 1/20

A

135.3 cm

d_A = 5.2 m

Offices (public =uncontrolledl)

B

T = 1

d_B = 4.7 m

d_G = 10.9 m

F

G

d_F = 7.7 m

T = 1

T = 1/10

Offices (public)

Equipment/ modulator (controlled)

d_D = 5.2 m

160.7 cm

d_C = 4.1 m

d_E = 6.5 m

D

E

Console area (controlled)

C

T = 1

Entrance (controlled)

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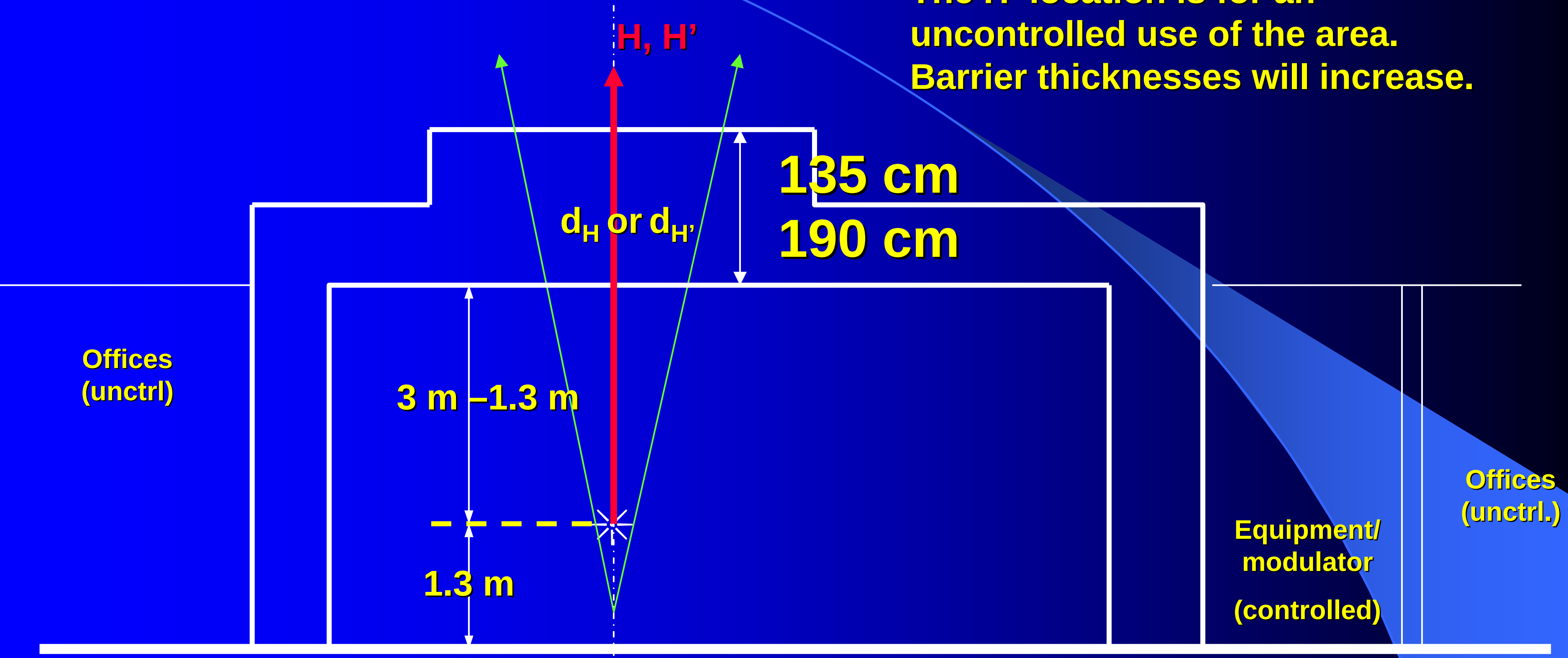
Example: 6 MV Therapy Vault---Up on the roof.

The H’ location is for an uncontrolled use of the area. Barrier thicknesses will increase.



H, H’

d_H or $d_{H'}$

135 cm

190 cm

Offices (unctrl)

3 m –1.3 m

1.3 m

Equipment/ modulator

(controlled)

Offices (unctrl.)

Important: Barrier width is determined by the beam divergence with gantry angle. Usually the width will match the primary barrier at the wall(s).

IDR, R_w, and R_h

For each (primary barrier) location it is recommended to verify the following quantities are acceptable:

R_W = Time-Averaged-Dose–Rate in a week = IDR* W_{pri} *U / DR_{1m}

where IDR = <u>transmitted</u> instantaneous dose rate = DR_{1m} B/d^2

→ R_w *x* T should not be > P

For public areas in Agreement States (NRC reg. → SSRs) regulations require an “in-any-one hour” constraint. Evaluate with:

R_h = Time-averaged dose in-any-one-hour

= (M/40) R_w where 40 hours of operation per week applies and

M = ratio of maximum # of patients treatable in an hour to the average #

For example, Avg# = 30 pts/8 h, or W_{pri} $(D_{average})^{-1}$ $(40\text{ h wk})^{-1}$

R_h should not be greater than 2 mrem or 20 μSv (“in-any-one-hour”)

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Location	IDR	R_w	R_wT	P	R_h	Limit	Applicable?	status
	mSv/h	mSv/wk	mSv/wk	mSv/ wk	mSv	mSv		
A	0.65	0.40	0.02	0.02	0.014	0.020	Yes	OK
C	0.16	0.10	0.10	0.10	0.003	(0.020)	No	OK
H	1.09	1.00	0.10	0.02	0.034	(0.020)	No	OK
H’	0.02	0.02	0.02	0.02	0.001	0.020	Yes	OK

Secondary Barriers

For leakage radiation barrier calculations use the equation

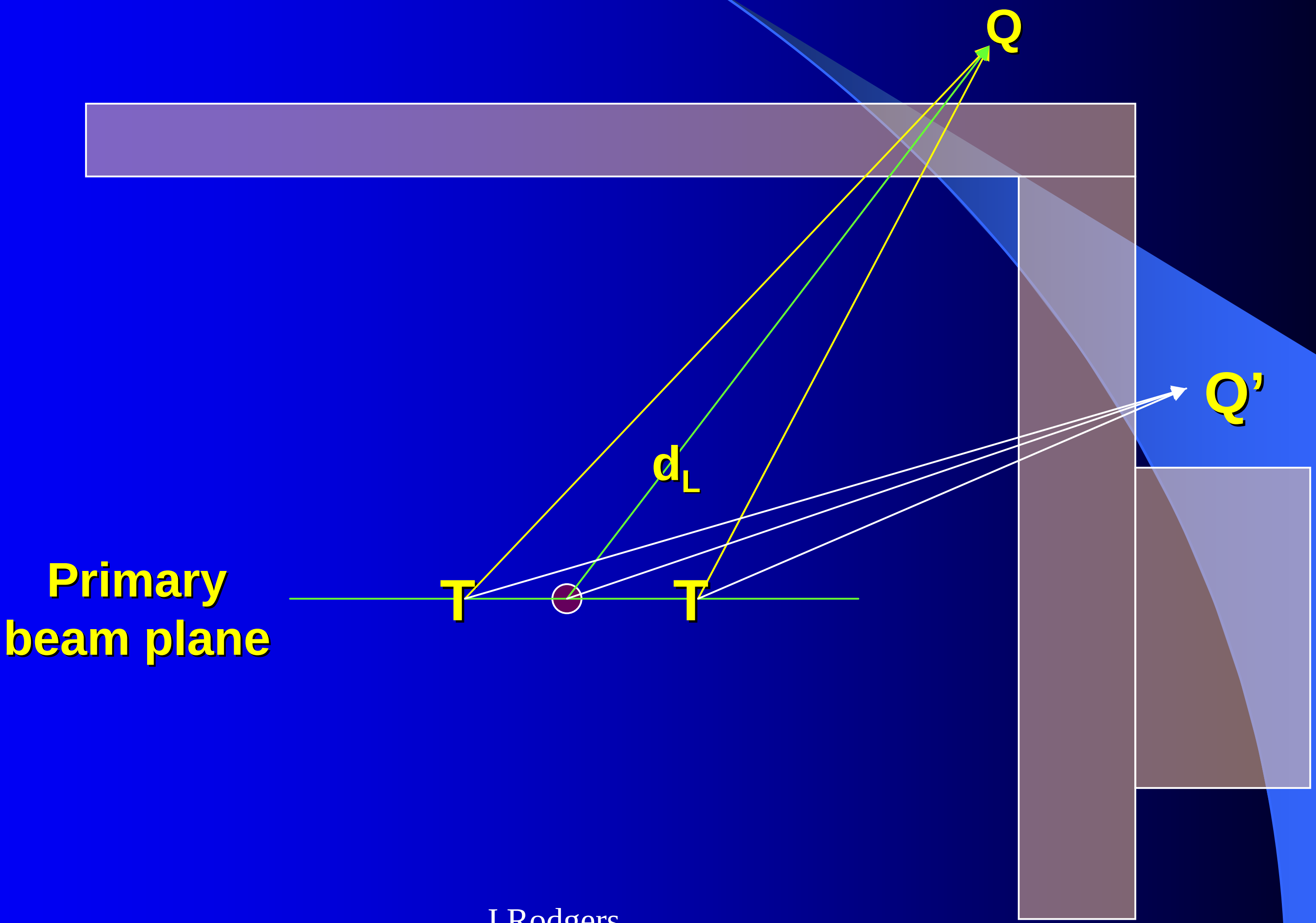
$P = 10^{-3} B_L W_L T/d_L^2$

1. Leakage radiation goes in all directions at roughly the same rate
2. ∴ For leakage radiation barriers, U is taken as 1 for many situations.

(significant departures from the U=1 approximation may occur)

…Shielding Calculation Methods for Medical…

Leakage Radiation to secondary barriers



Secondary Barriers

…Leakage Radiation to secondary barriers

Leakage radiation is proportional to the total number of MU the machine produces per week.

Thus, the workload for leakage, W_L, will be larger than W_{pri} when IMRT, stereotactic radiosurgery and TBI procedures are being performed.

In particular, for (100%) IMRT:

$$W_L = C_I * W_{pri}$$

Where C_I is the ratio of average of # MU using IMRT to the average MU without IMRT

C_I varies from 2 to 15 in current technology.

Secondary Barriers

---Leakage Radiation

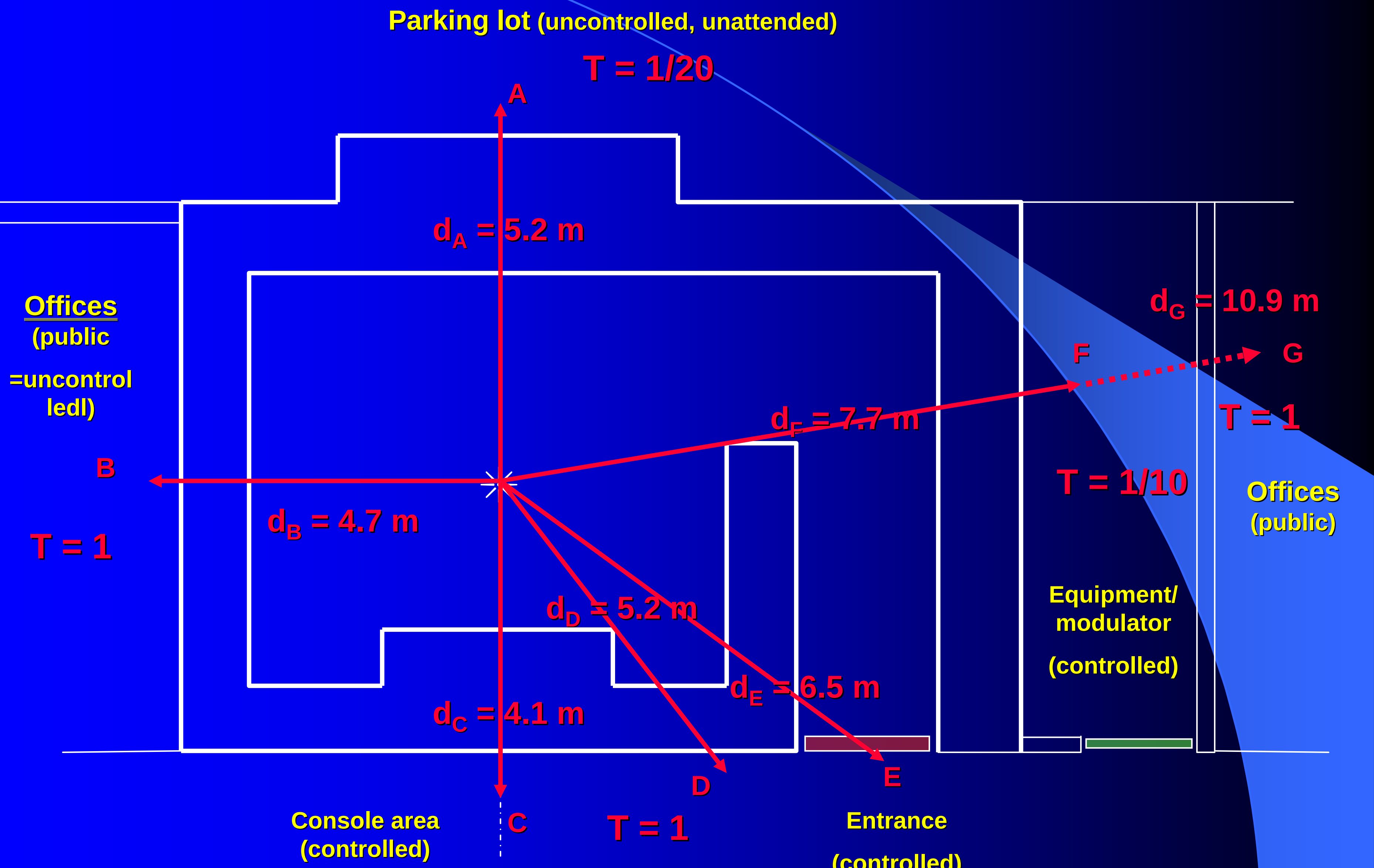
For our example, we will use $C_l = 4$ and assume the accelerator will be used with IMRT for 75% of the patients.

Thus, the leakage workload is:

$$W_L = 0.75{*}C_l{*}W_{pri} + 0.25\ W_{pri} = 3.25 \times W_{pri}$$

$$= 2373\ \text{Gy/wk}$$

Example: 6 MV Therapy Vault



Parking lot (uncontrolled, unattended)

T = 1/20

A

d_A = 5.2 m

Offices

(public

=uncontrol
led)

B

T = 1

d_B = 4.7 m

d_F = 7.7 m

F

G

d_G = 10.9 m

T = 1

T = 1/10

Offices
(public)

Equipment/
modulator

(controlled)

d_D = 5.2 m

d_E = 6.5 m

d_C = 4.1 m

D

E

C

Console area
(controlled)

T = 1

Entrance

(controlled)

J Rodgers

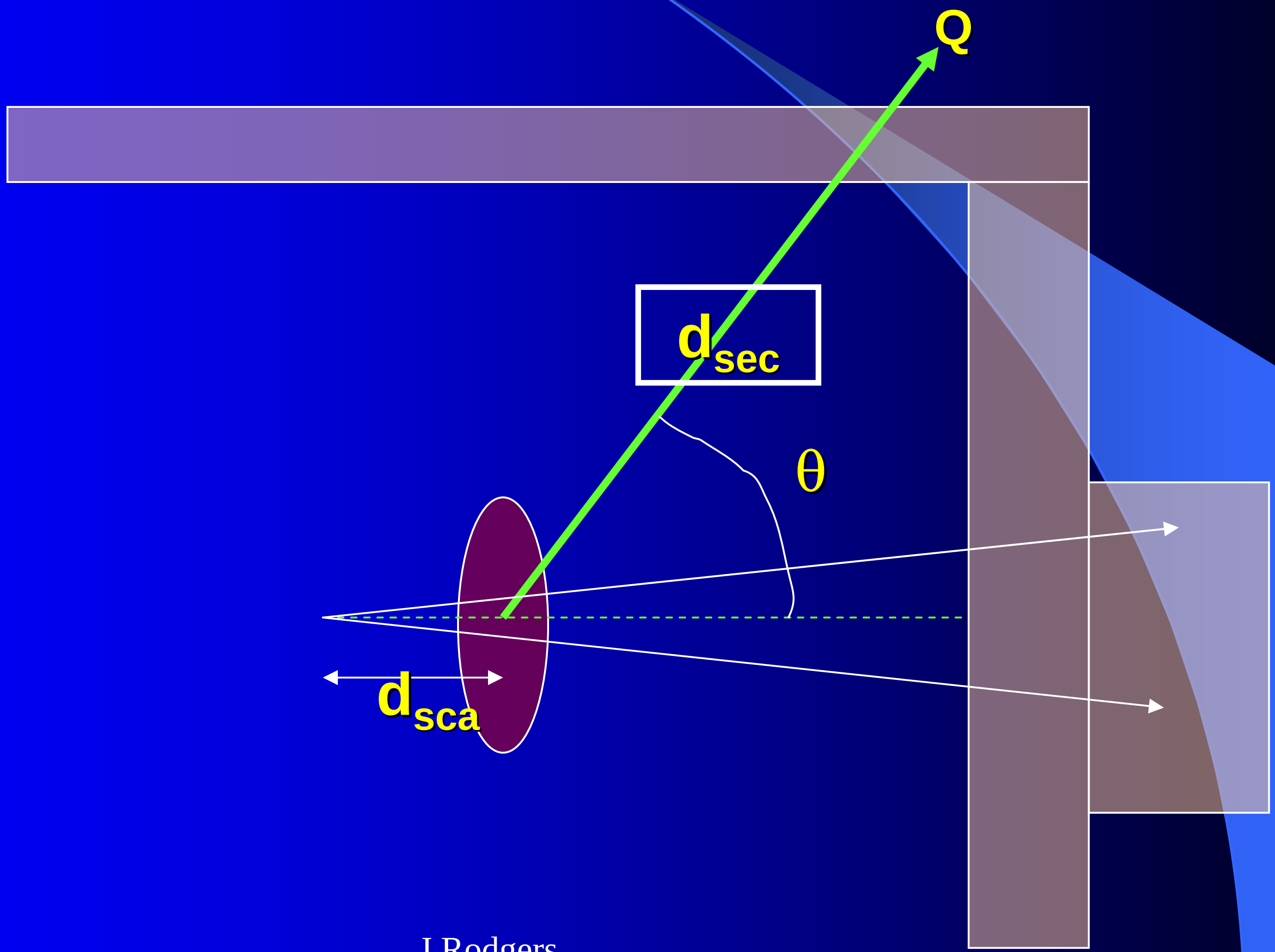
…Leakage Radiation to secondary barriers

MV	Material	Leakage TVLs TVL_1/TVL_e (cm)
6	Concrete	34/29
18	Concrete	36/34

NCRP 151, Table B.7

…Shielding Calculation Methods for Medical…

Scatter radiation arises from two principal sources—the patient and barriers. We deal with patient scatter first.



…Shielding Calculation Methods for Medical…

…Scatter radiation to Secondary barriers

We set $P(@Q) = B_{sca}\ H_{sca}$

$$= B_{sca}\ [W_{pri}\ U(Q)\ T/d_{sca}^{2}\ ]*[a(\theta)/d_{sec}^{2}\ ]*F/400cm^{2}$$

Scattered radiation is normally much less penetrating than primary (especially for megavoltage x-rays at wide angles).

Exceptions to this may occur when $\theta \leq 20°$.

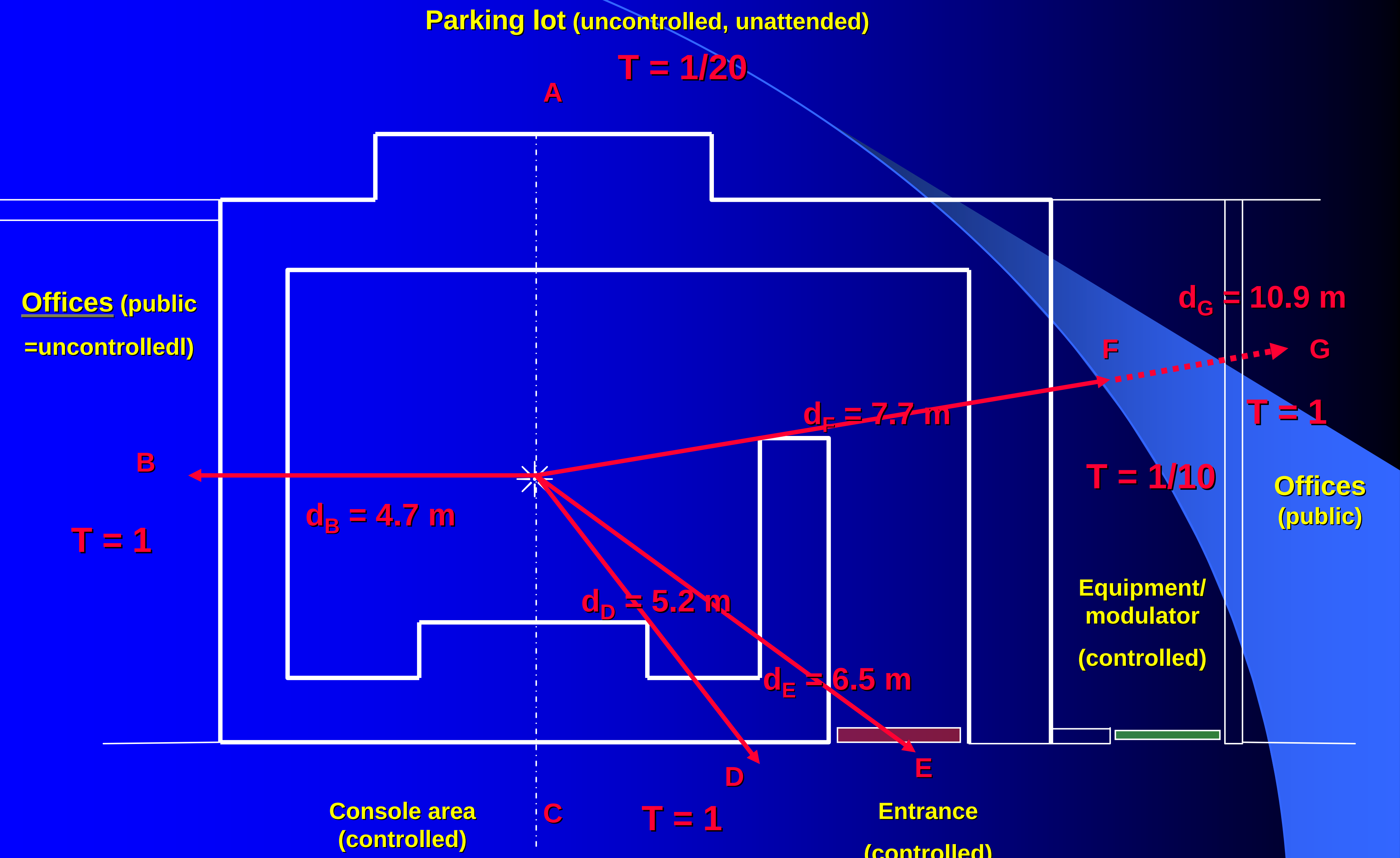
…Shielding Calculation Methods for Medical…

Scatter radiation to Secondary barriers

NCRP 151 TABLES B.4 and B.6

θ (deg)	a(θ)	Mean energy (MeV)
10	$1.04\text{x}10^{-2}$	1.4 (1.6 at 0°)
20	$6.73\text{x}10^{-3}$	1.2
30	$2.77\text{x}10^{-3}$	0.9
45	$1.39\text{x}10^{-3}$	0.6
60	$8.24\text{x}10^{-4}$	0.45
90	$4.26\text{x}10^{-4}$	0.2
135	$3.00\text{x}10^{-4}$	0.2
150	$2.87\text{x}10^{-4}$	<0.2

Example: 6 MV Therapy Vault



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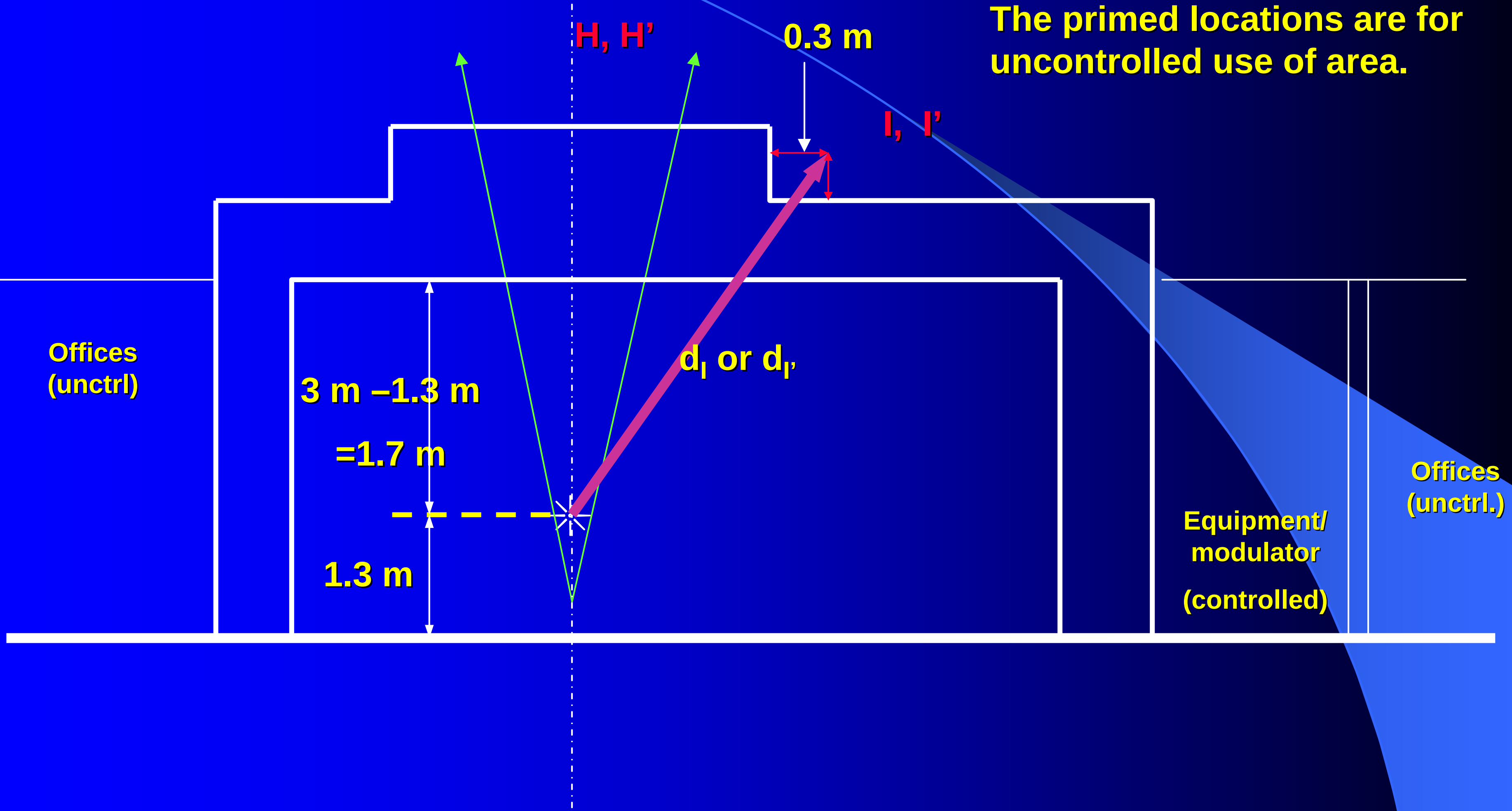
Example: 6 MV Vault---Roof Secondary.

The primed locations are for uncontrolled use of area.



H, H'

0.3 m

I, I'

Offices (unctrl)

3 m –1.3 m

=1.7 m

1.3 m

d_I or $d_{I'}$

Equipment/ modulator

(controlled)

Offices (unctrl.)

Thicknesses required for Leakage Radiation (alone)

location	Type	P	T	d	B_L	n(L)	t_L
		mSv/wk		m			cm
B	**Unctrl.**	0.02	1	**4.7**	1.85e-4	3.73	**113.2**
D	**Crtl.**	0.10	1	**5.2**	1.13e-3	2.94	**90.4**
E	**Ctrl.**	0.10	1	**6.5**	1.77e-3	2.75	**84.7**
F	**Ctrl.**	0.10	0.1	**7.7**	2.48e-2	1.60	**51.6**
G	**Unctrl.**	0.02	1	**10.9**	9.94e-4	3.00	**92.0**
I	**Ctrl.**	0.10	0.1	**3.3**	4.56e-3	2.34	**72.8**
I’	**Unctrl.**	0.02	1	**3.7**	1.15e-4	3.94	**119.2**

Thicknesses required for Scattered Radiation (alone)

location	Type	P	T	a(θ)	B_{sca}	n(sca)	t_{sca}
& (θ)		mSv/wk					cm
B(90°)	**Unctrl.**	0.02	1	**4.26e-4**	1.42e-3	2.85	**48.4**
D (40°)	**Crtl.**	0.10	1	**2.10e-3**	1.76e-3	2.75	**66.1**
E (55°)	**Ctrl.**	0.10	1	**1.00e-4**	5.79 e-2	1.24	**27.2**
F (90°)	**Ctrl.**	0.10	0.1	**4.26e-4**	1.91e-1	0.72	**12.2**
G (90°)	**Unctrl.**	0.02	1	**4.26e-4**	7.64 e-3	2.12	**36.0**
I (50°)	**Ctrl.**	0.10	0.1	**1.20e-3**	1.24e-2	1.91	**41.9**
I' (50°)	**Unctrl.**	0.02	1	**1.20e-3**	3.13e-4	3.51	**77.1**

I have taken F/400 $cm^2 \approx 1$ for this mainly IMRT machine.

Combine the results from leakage and scatter calculations at each secondary barrier location:

The rule of thumb is that if the difference between the two thicknesses obtained by the independent (e.g., leakage and scatter) calculations is > 1 TVL(of the more penetrating radiation) , then use the larger thickness.

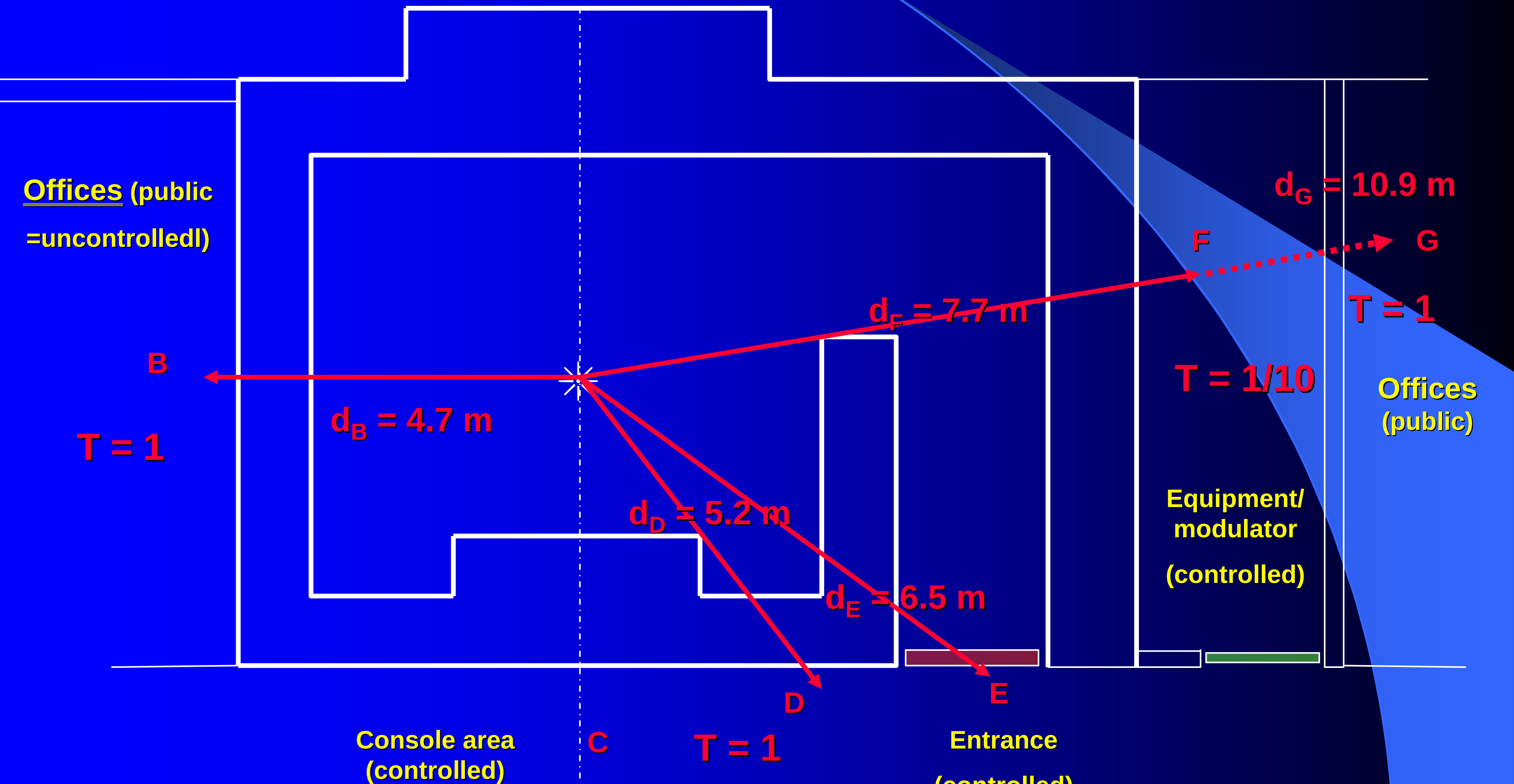
If not (> 1 TVL), add 1 HVL (0.30 TVL) of the more penetrating radiation to the larger thickness.

Secondary Barrier-- Combined Results

Location	t_L -t_{sca}	>1TVL$_e$(L)?	"old t"	"new t"	x = cos(ang) *t
	cm		cm	cm	cm
B	64.8	Yes	113.2	113.2	113.2
D	24.3	No	90.4	99.1	76.0
E	57.5	Yes	84.7	84.7	48.6#
F	39.3	Yes	51.5	51.5	51.5
G	56.0	Yes	92.0	92.0	92.0
I	30.9	Yes	72.8	72.8	46.8
I'	42.1	Yes	119.2	119.2	76.6

maze barrier thickness

Example: 6 MV Therapy Vault



Parking lot (uncontrolled, unattended)

T = 1/20

A

Offices (public =uncontrolledl)

d_G = 10.9 m

F

G

d_F = 7.7 m

T = 1

B

T = 1/10

Offices (public)

d_B = 4.7 m

T = 1

Equipment/ modulator (controlled)

d_D = 5.2 m

d_E = 6.5 m

D

E

Console area (controlled)

C

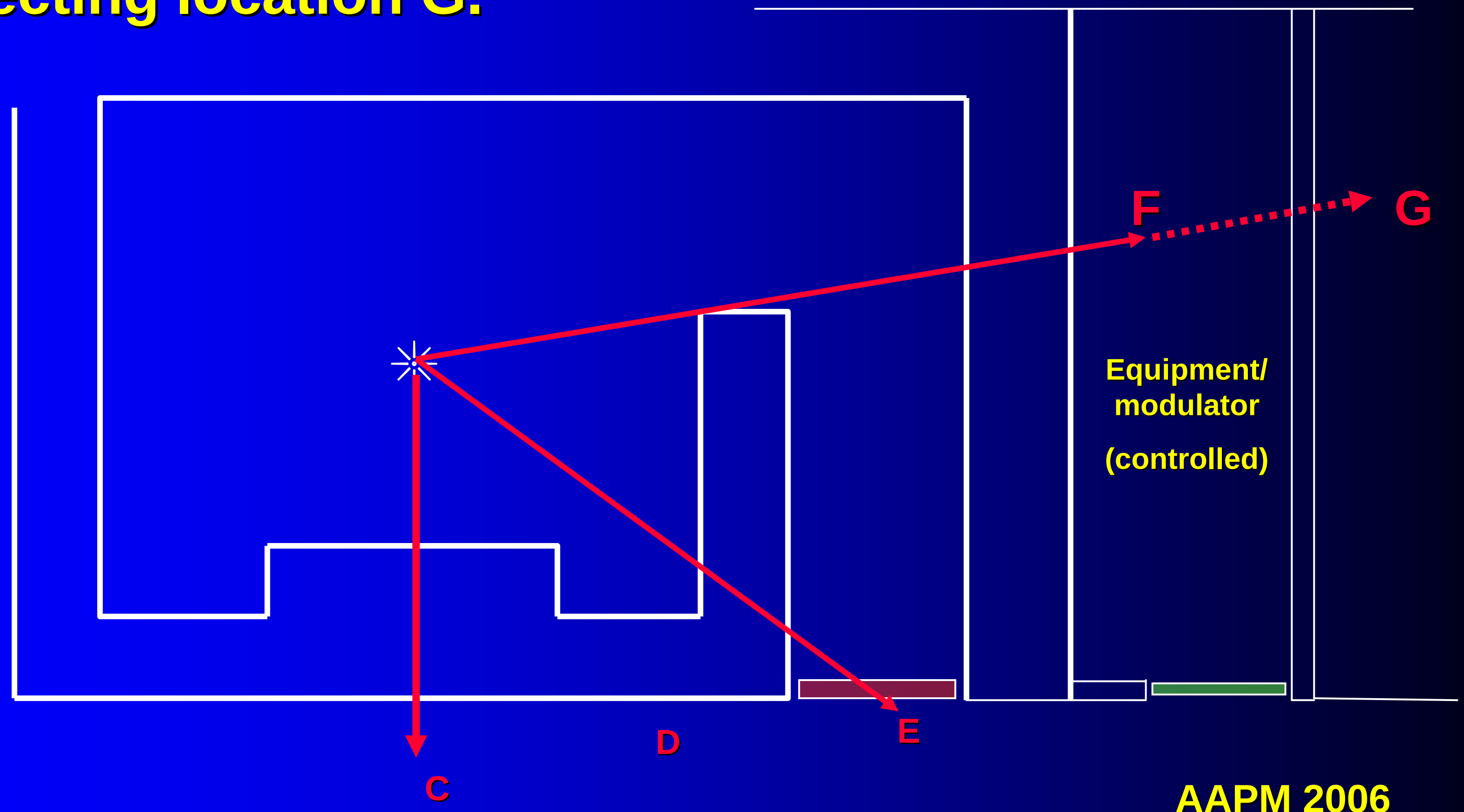
T = 1

Entrance (controlled)

Houston, we have a problem!

The barrier thickness required for location G (92 cm) exceeds the barrier thickness (51.5 cm) for location F.

However, there is no additional barrier beyond “F” protecting location G.



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Houston, what do we do?

This is not an uncommon problem when a uncontrolled location is just on the other side of a controlled location.

Solution: Add 40.5 cm (92-51.5) of concrete to barrier F, giving it the thickness of 92 cm.

Alternatively, declare location F as uncontrolled.

Note: Putting T = 1 at location F, still does not solve this problem.

IDR, R_w and R_h Evaluations for Secondary Barriers

The weekly Time-Averaged-Dose-Rate (R_w) for leakage and scatter radiations is computed as follows:

$$R_w = R_w(L) + R_w(sca)$$

(prospectively) $R_w = 10^{-3} W_L \, B_L/d_L^2 + a(\theta) \, [F/400] W_{pri} \, U(\theta) \, B_{sca} / d_{sec}^2$

The barrier transmission factors are (re)computed with the final thicknesses

(retrospectively) $R_w = [IDR_L \, W_L / DR_0] + [IDR_{ps} \, W_{ps} \, U/DR_0]$

where $IDR_{ps} = IDR_{total} - IDR_L$

J Rodgers

IDR, R_w and R_h Evaluations for Secondary Barriers

As for primary barriers we have:

$$R_h = (M/40)\ R_w$$

IDR, R_w and R_h Evaluations for Secondary Barriers

location	R_w T	P	P ≥ R_wT ?
	mSv/wk	mSv/wk	
B	0.02	0.02	Yes
D	0.05	0.10	Yes
E	0.10	0.10	Yes
F	0.10	0.10	Yes
G	0.02	0.02	Yes
I	0.10	0.10	Yes
I’	0.02	0.02	Yes

IDR, R_w and R_h Evaluations for Secondary Barriers

Location	IDR$_L$	IDR$_{sca}$	IDR$_{tot}$	R_h	Limit	Applicable?	status
	μSv/h	μSv/h	μSv/h	μSv	μSv		
B	**2.0**	**0.0**	**2.0**	**1.0**	**20**	**Yes**	**OK**
D	**5.0**	**1.4**	**6.4**	**2.0**	**(20)**	**No**	**OK**
E	**10**	**0.1**	**10.1**	**3.0**	**(20)**	**No**	**OK**
F	**101.**	**1.6**	**102.6**	**34**	**(20)**	**No**	**OK**
G	**2.0**	**0.0**	**2.0**	**1.0**	**20**	**Yes**	**OK**
I	**101**	**13.0**	**114**	**35**	**(20)**	**No**	**OK**
I’	**2**	**0.1**	**2.1**	**0.7**	**20**	**Yes**	**OK**

EXAMPLES

- 6 MV Vault--Primary and Secondary Barriers
- Low Energy Maze Entrance/Door
- High Energy Maze Door
- TBI Considerations
- Robotic SRS Machine

Low Energy Maze Entrance--Door

Contributions at door:

Pri. scattered to maze wall to door (H_S)

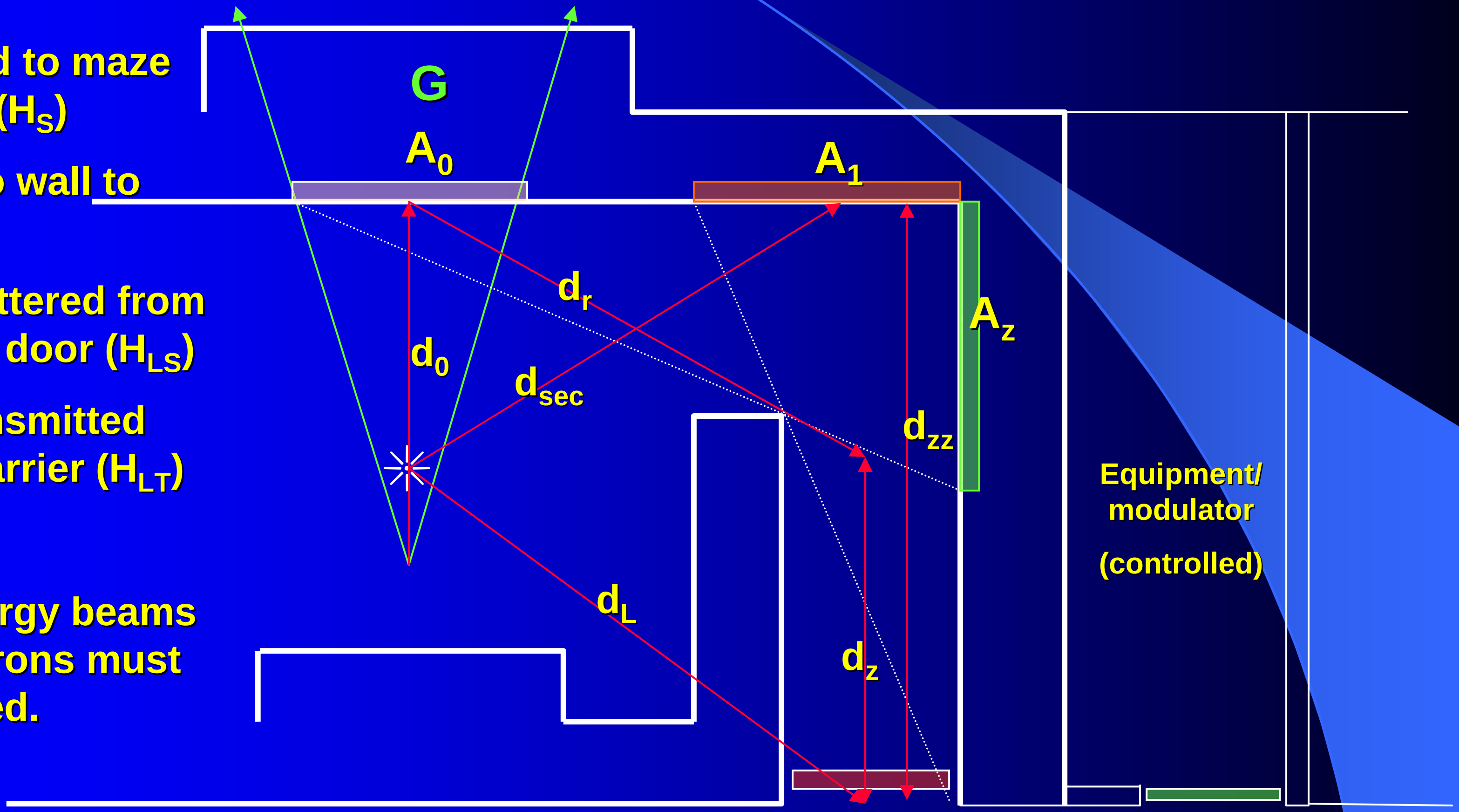
Pt. Scatter to wall to door (H_{PS})

Leakage scattered from maze wall to door (H_{LS})

Leakage transmitted thru maze barrier (H_{LT})

…….

For high energy beams photon neutrons must be considered.



The Maze Door---Low energy

For a specific gantry orientation (G) we have

$$H_G = f^*H_S + H_{PS} + H_{LS} + H_{LT}$$

And $H_{Tot} = 2.64\ H_G$

H_S = primary scattered from barrier to wall to door

$$= [W_{pri}\ U_G /d_0^2]\ [\alpha_0 A_0/d_z^2]\ [\alpha_z(0.5\ \text{MeV})A_z/d_r^2]$$

α is a reflection or differential-albedo coefficient

the distances (m) are indicated in the Figures

f is the fraction of primary transmitted through patients (~0.25 for low energy beams)

The Maze Door---Low energy

H_{PS} = scatter from patient to maze wall, then scattered to door

$= [W_{pri}\ U_G/d_{sca}^2]\ [a(\theta)\ (F/400)/d_{sec}^2]\ [\alpha_1 A_1/d_{zz}^2]$

H_{LS} = leakage radiation scattered from (maze walls) to door

$= [10^{-3}\ W_L\ U_G/\ d_{sec}^2]\ [\alpha_1 A_1/d_{zz}^2]$

And

H_{LT} = leakage radiation transmitted through maze barrier to door

$= 10^{-3}\ W_L\ U_G\ B_L(G)/d_L^2$

Here d_L is the distance from x-ray target to door for gantry orientation G.

Example: 6 MV Therapy Vault--Door

A_0 =(2.6 m)^2

= 6.8 m^2

A_1 =(2.9 m)x(3m)

= 8.7 m^2

A_z = 9.3 m^2

d_0 = 4.0 m

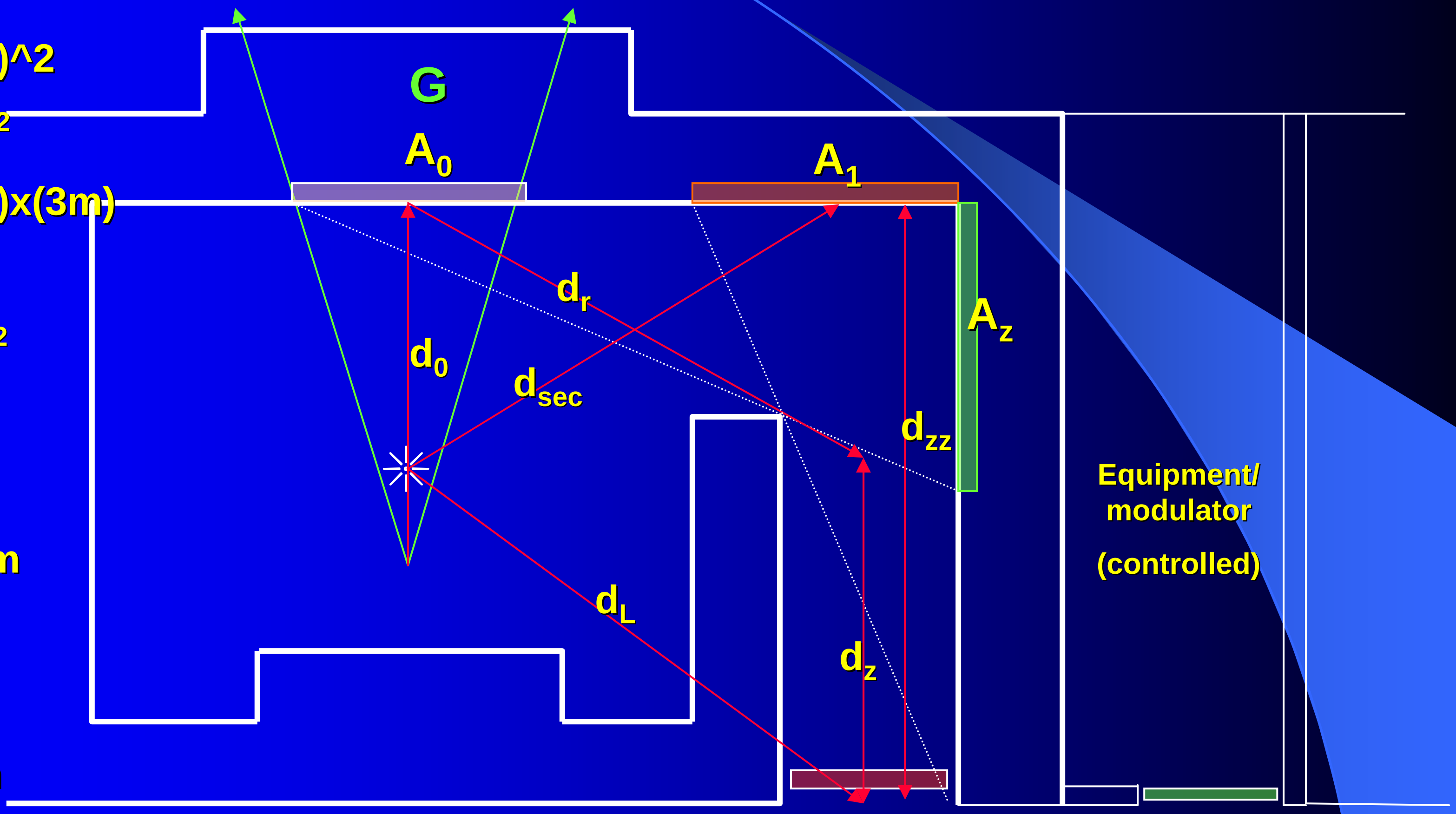
d_r = 5.8 m

d_{sec} = 5.5 m

d_L = 6.2 m

d_z = 3.9 m

d_{zz} = 6.6 m



Entrance

(controlled)

Example: 6 MV maze door

H_S = 0.0223 mSv/wk

H_{PS} = 0.0051 mSv/wk

H_{LS} = 0.0200 mSv/wk

H_{LT} = 0.0220 mSv/wk

H_G = 0.0324 mSv/wk (using f = 0.25)

H_{Tot} = 2.64 *H_G = 0.0856 mSv/wk

H_{Tot} < P = 0.10 mSv/wk

H_{Tot} is just below the design goal.

Example: 6 MV maze door

However, to ensure that P is met, it is suggested that the door have some lead added to it.

Figure 3-6 from McGinley’s book gives the amount of Pb needed in the maze door.

To lower the DE by 2 HVLs we need about 1 mm of Pb.

Data for Pb door (McGinley)

Conventional Maze Design · 53

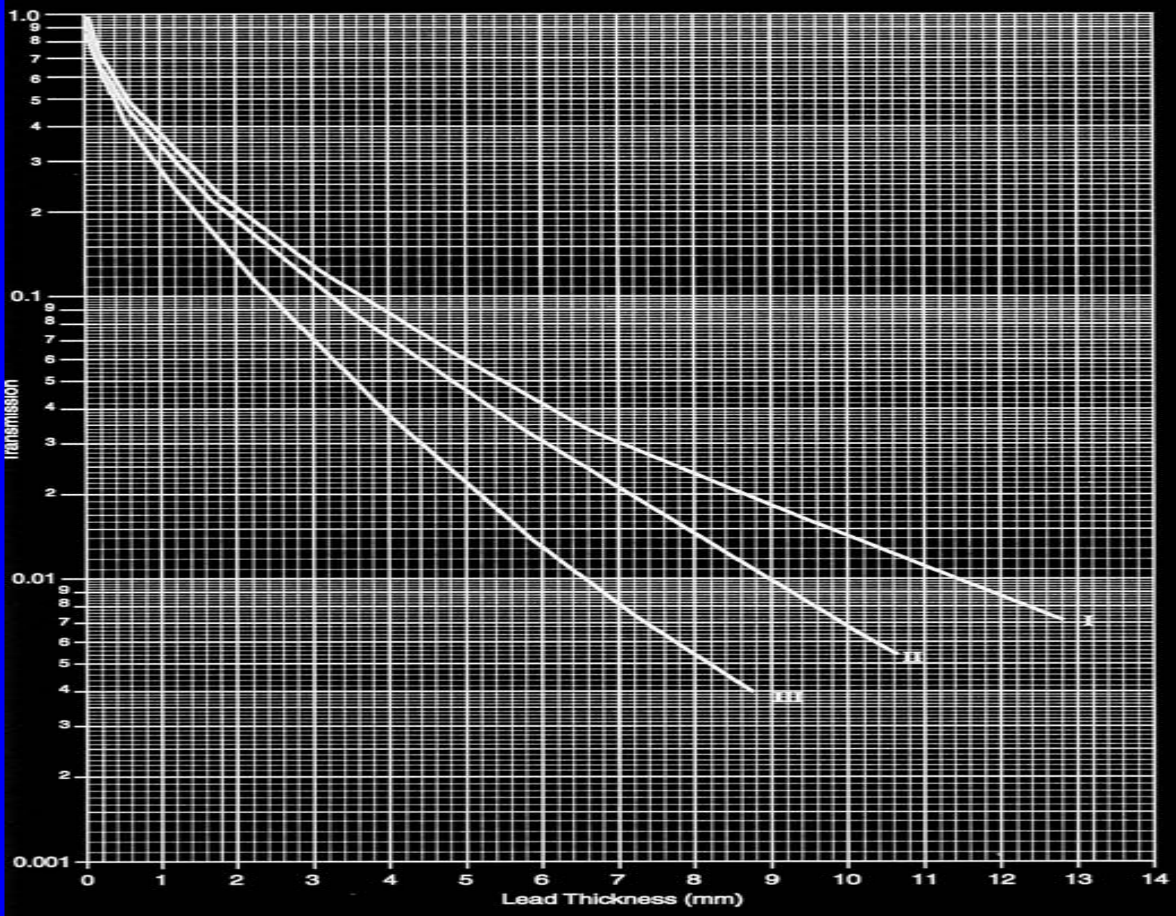


Figure 3-8. Transmission through lead of the radiation field in the maze of a 6 MeV accelerator facility with the beam aimed at wall C. The maze lengths for curves I, II, and III are 1.5 m, 2.0 m, and 3.4 m, respectively.

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EXAMPLES

- 6 MV Vault--Primary and Secondary Barriers
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High Energy (>10 MV) Machines

The determination of primary and secondary barriers is essentially the same as for low energy.

In addition, the photon shielding in those barriers is normally adequate for photoneutrons.

Photoneutrons do present additional dose equivalent contributions at the maze door.

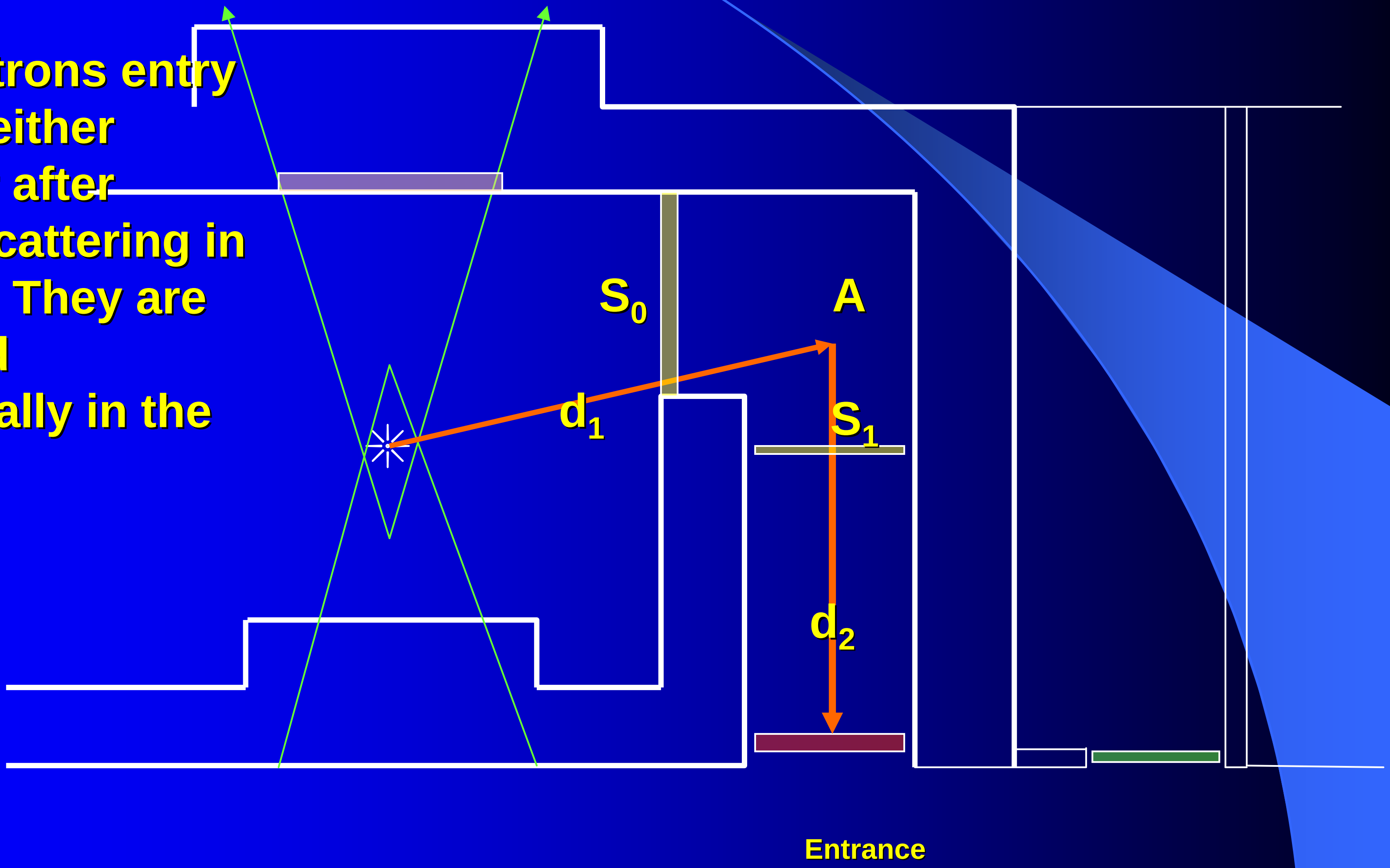
There are two principal sources of DE at the door:

1. Scattered neutrons (fast to thermal)
2. neutron-capture gamma-rays

Photoneutron Scatter to the Maze Door

Contributions at door:

Photoneutrons entry the maze either directly or after multiple scattering in the room. They are attenuated exponentially in the maze.



Photoneutron DE at the door

The Kersey method and a modified Kersey formula:

The neutron DE per week at the door is $H_n = W_L \; H_{K \text{ or } MK}$

(Kersey) $H_K = H(d_o) \; (S_0/S_1) \; (d_o/d_1)^2 \; 10^{-[d_2 / TVD]}$

where d_o = 1.41 m is measured from the x-ray target

$H(d_o)$ is the measured total n-DE at d_o

and TVD = 5 m is the recommended tenth value distance

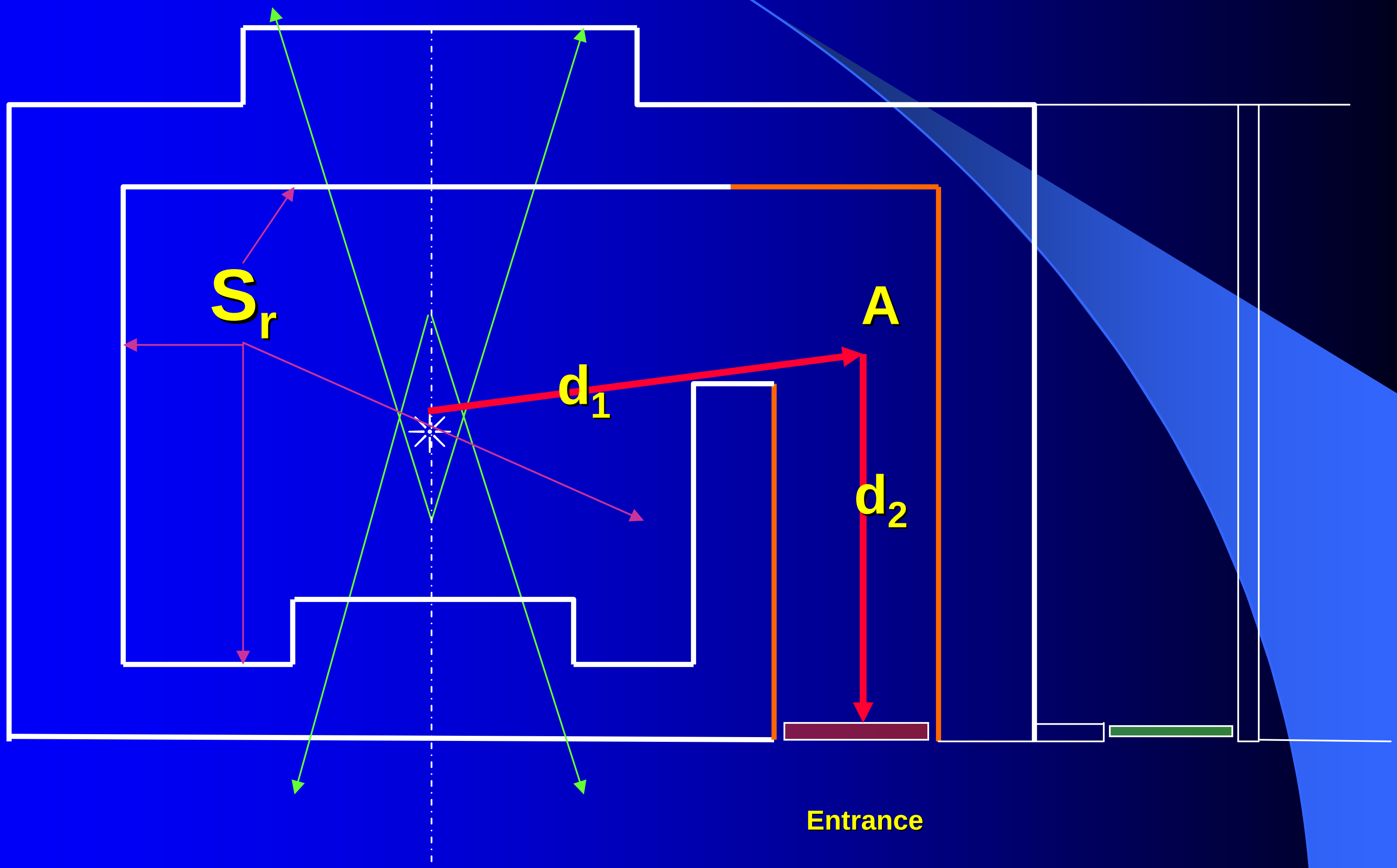
S_0 and S_1 are defined in the previous Figure

Or, Modified-Kersey (Wu and McGinley):

$$H_{MK} = 2.4 \times 10^{-15} \; \varphi_A \; (S_0/S_1)^{0.5} \; [1.64 \times 10^{-[d_2 /1.9]} + 10^{-[d_2 / T_N]}]$$

where $T_N = 2.06 \; (S_1)^{0.5}$ is a TVD for fast neutrons

High Energy Capture Gamma Problem



Entrance

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The Capture Gamma DE at the Maze Door

Formulas:

$H_{cg} = W_L \, h_\varphi$, [in Sv/wk at door]

$h_\varphi = K \, \varphi_A \, 10^{-[d_2 / TVD]}$, [in neutron-Sv / photon-Gy]

$\varphi_A = \beta Q_n/(4\pi d_1^2) + 5.4 \beta Q_n/(2\pi S_r) + 1.3 \beta Q_n /(2\pi S_r)$, [in $n/(m^2 Gy)$]

$K = 6.9 \times 10^{-16}$ m^2 Sv/n

TVD = tenth-value distance, ≈ 5.4m for 18-25 MV x-rays,

≈3.9 m for 15 MV x-rays

Q_n = neutrons produced per photon-Gy

β= fraction of fast neutrons transmitted thru accelerator shielding

(=1 for Pb, = 0.85 for W)

S_r = surface area of room (m^2)

Example :Photoneutron→ maze door

18 MV X-ray machine

Data

d_1 = 6.4 m

d_2 = 8.5 m

S_0 = 9.2 m^2

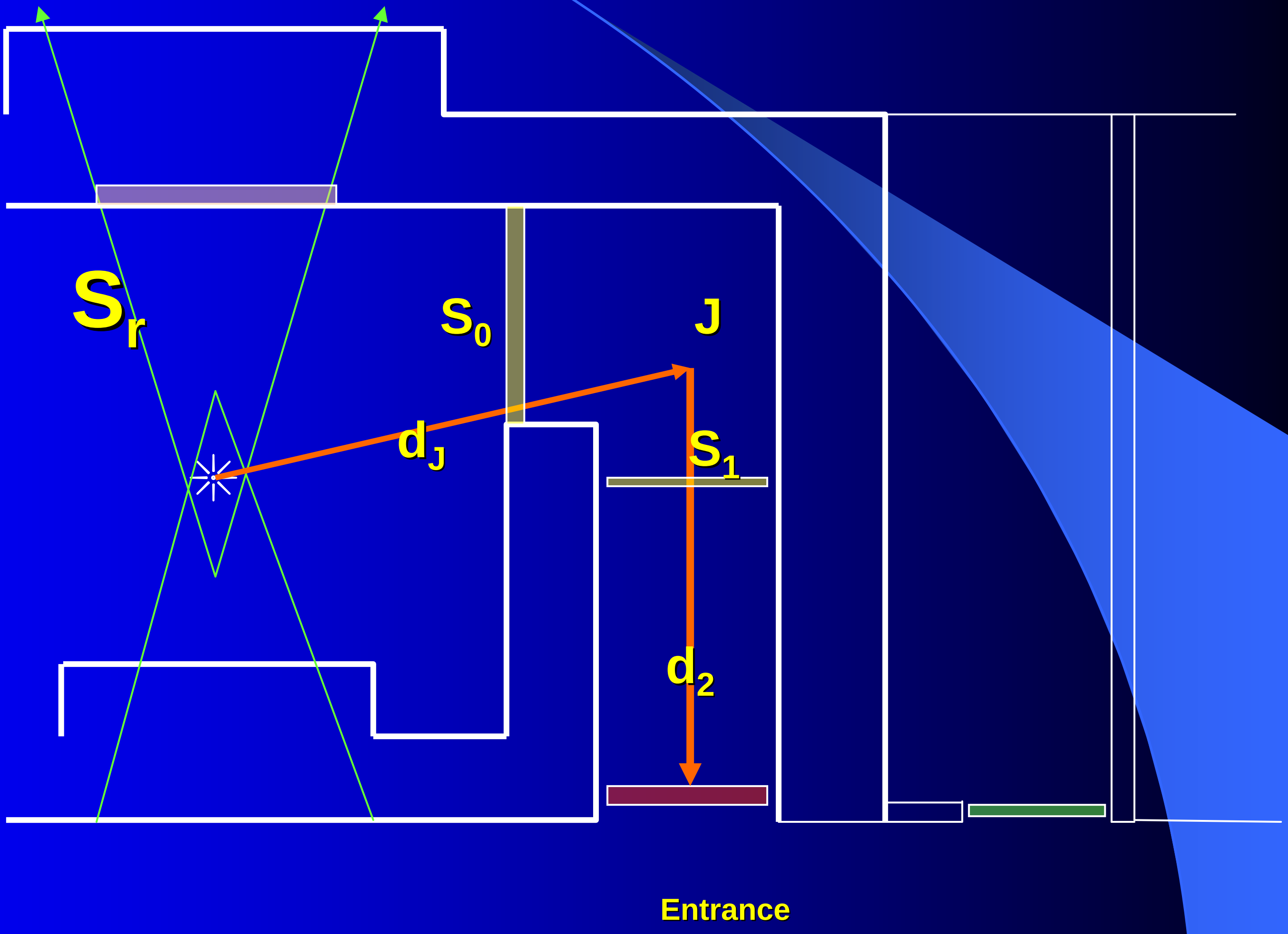
S_1 = 8.4 m^2

S_r = 236 m^2

W_L (40% IMRT)
= 5*450(40%) Gy/wk +

(60%)*450 Gy/wk

=1170 Gy/wk



Example-Results 18 MV

Kersey's formula (as modified by McGinley)

$H_K = H(d_o)\ (S_0/S_1)\ (d_o/d_1)^2\ 10^{-[d_2\ /\ 5]}$

$H_K =$ $1.7\text{x}\ 10^{-3}$ mSv/Gy

here $H_0 = 1.6$ mSv/Gy at $d_0 = 1.41$ m

Modified Kersey---Wu-McGinley formula:

$H_{MK} = 2.4\text{x}10^{-15}\ \varphi_A\ (S_0/S_1)^{0.5}\ [1.64\text{x}10^{-[d_2\ /1.9]} + 10^{-[d_2\ /\ TVD\ ]}\ ]$

$TVD = 2.06\ (S_1)^{0.5} = 6$ m

$\varphi_J = \beta\ Q_n/(4\pi\ d_1{}^2) + 5.4\ \beta\ Q_n/(2\pi S_r\ ) + 1.3\ \beta\ Q_n\ /(2\pi S_r\ )\ ,\ \ [n/(m^2Gy)]$

$\beta = 1$ for Pb, $Q_n = 1.22\ \text{x}10^{12}$ n/Gy

$\varphi_A = 7.88\ \text{x}10^9$ n /(m^2 Gy),

$H_{MK}=$ $0.8\ \text{x}10^{-3}$ mSv/Gy

Example-Results 18 MV

Kersey's formula gives a larger H value than modified Kersey by a factor of 2.2. The MK has a large amount of good recent data to support it.

What to do? Could take the average or, more conservatively, use the larger value. → $H = 1.7 \times 10^{-3}$ mSv/Gy

The photoneutron DE per week at the door is estimated as:

$H_n = W_L {}^{*}H = (1170 \text{ Gy/wk})(1.7 \times 10^{-6} \text{ Sv/Gy}) \approx 1.99 \text{ mSv/wk}$

The Capture Gamma contribution at the door:

$H_{cg} = W_L\ h_\varphi$, [in Sv/wk at door]

$h_\varphi = K\ \varphi_A\ 10^{-[}d_2 / \text{TVD}]$, [in neutron-Sv / photon-Gy]

$K = 6.9 \times 10^{-16}\ \text{m}^2$ Sv/n

TVD = tenth-value distance, ≈ 5.4m for 18-25 MV x-rays,

$h_\varphi = 0.145$ E-06 Sv/Gy

Hcg = .170 mSv/wk

Example-Results 18 MV

Combining all DE contributions at the maze door, we have

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

where $H_n = W_L {}^{*}H = 1.99$ mSv/wk

Hcg = 0.17 mSv/wk

& H_{tot} = photon (x-ray) contribution,

calculated elsewhere ≈ 0.11 mSv/wk

So, the total neutron DE at the door, 2.3 mSv/wk, requires door shielding (Polyethylene and Pb).

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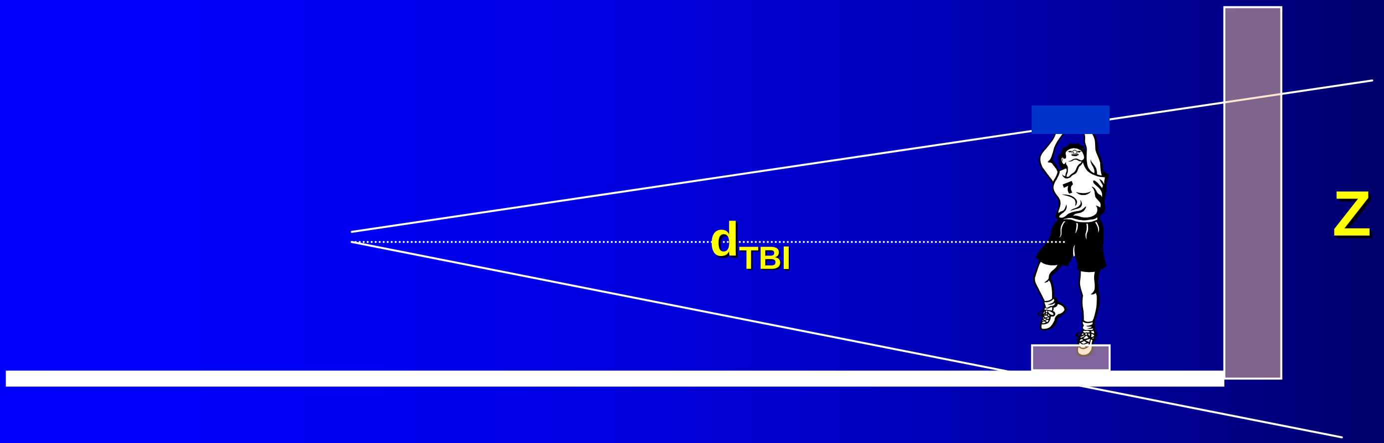
TBI Considerations

The extended treatment distance, d_{TBI} , can significantly increase the workloads (primary and leakage) at 1 m.

e.g., $W_{TBI} = D_{TBI}\, d_{TBI}^2$

d_{TBI}, typically, ranges from 4-6 m from the x-ray target.

This increase in the primary workload only affects the “TBI” barrier, whereas the leakage radiation increase applies to all barriers.



The workloads are the principal changes needing consideration in this situation.

1. If d_{TBI} = 4 m and D_{TBI} = 2 pt/wk *12 Gy/pt = 24 Gy/wk, then

then the TBI contribution to the primary workload at 1 m is

W_{pri}(TBI) = 16 x 24 = 384 Gy/wk

The leakage radiation contribution at 1 m is W_L(TBI) = W_{pri}(TBI) .

2. Next, assume that 35 patients are treated conventionally.

W_{pri}(conv) = 35 pt/day (2.5 Gy/pt)(1/0.6)(5 day/wk) = 730 Gy/wk

& W_L(conv) = W_{pri}(conv)

3. Combined TBI and conventional workloads are:

Directed at location Z (beyond the TBI barrier) is

$W_{pri}(Z) = U(conv)*W_{pri}(conv) + W_{pri}(TBI) = .2 *730+ 384$

$= 146 +384 = \underline{530\ Gy/wk}$

and the leakage radiation workload for <u>all</u> barriers is:

$W_L = W_L(conv) + W_L(TBI) = 730 + 384 = \underline{1114\ Gy/wk}$

4. We now allow that 40 % of the (conventional) patients are treated using IMRT. Take $C_l = 4$ as in prior example.

The primary workload directed at Z remains the same, 530 Gy/wk, and workloads of 730 Gy/wk*U are directed toward other primary barriers.

The leakage radiation workload increases as follows:

$$[W_L(\text{conv})+W_L(\text{IMRT})] = f_{IMRT}*C_l*W_{pri}(\text{conv})+(1- f_{IMRT})\, W_{pri}(\text{conv})$$

$$= 0.4(4)(730) + 0.6(730)$$

$$= 2.2*730 = 1606 \text{ Gy/wk}$$

Thus, the total leakage radiation workload to be applied to all barriers is:

$$W_L(\text{total}) = W_L(\text{TBI}) + [\, W_L(\text{conv}) + W_L(\text{IMRT})]$$

$$= 384 + 1606 = 1990 \text{ Gy/wk}$$

5. Evaluation of R_h is especially needed due to the long treatment time per fraction.

EXAMPLES

- 6 MV Vault--Primary and Secondary Barriers
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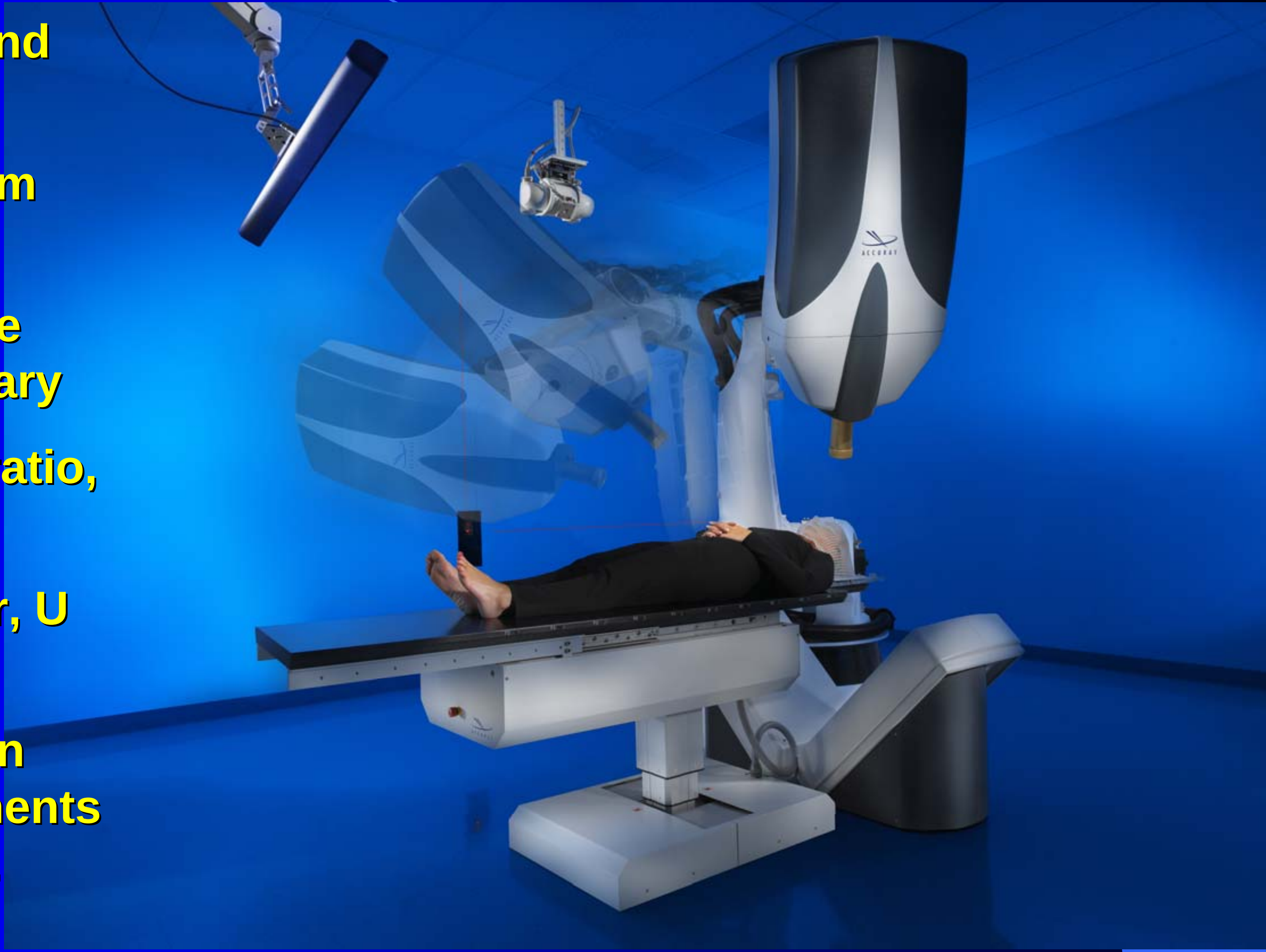
- **Robotic SRS Machine**

The CyberKnife

- ♠ SRS-cranial and extracranial
- ♠ 2.5 π ste. beam access
- ♠ All barriers are potentially primary
- ♠ High “IMRT” ratio, C (≈15)
- ♠ Low use factor, U
- ♠ ∴ Leakage & primary radiation barrier requirements are comparable.



More CK Information

Analysis* of Georgetown University Hospital CyberKnife patient plan data yielded the following:

1. U =0.05, is a conservative use factor
2. C_I = 15 is an average ratio of MU to cGy
3. The average dose delivered per session is 12.5 Gy
4. The average # of treatment sessions (fractions or stages) is 3.2 per lesion. Range: 1-5

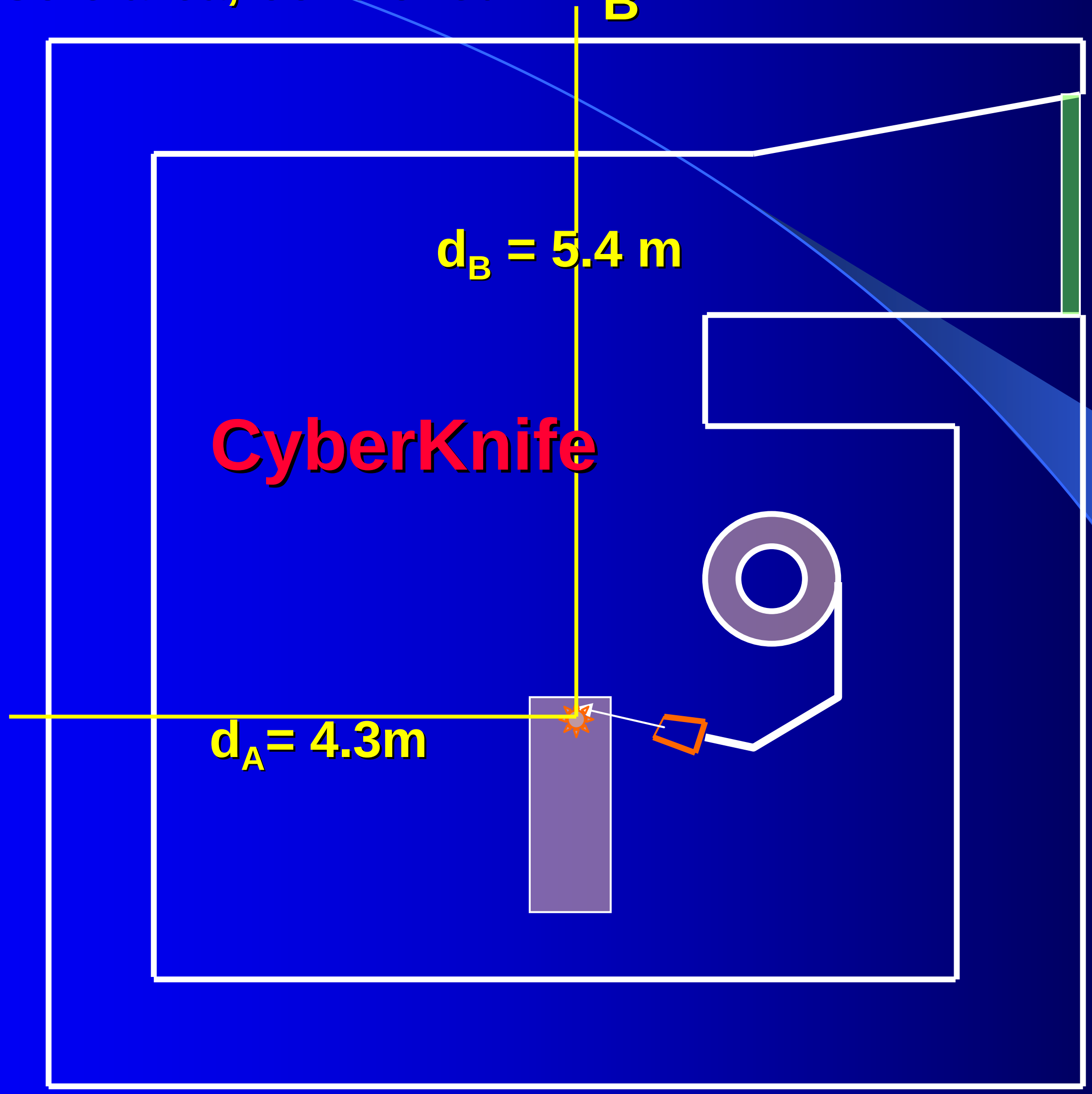
Also,

6 treatment sessions per 8 hour day is typical.

*James Rodgers, CyberKnife Treatment Room Design and Radiation Protection, Chapter 5, Robotic Radiosurgery, Vol.1, (CyberKnife Society Press, Sunnyvale, CA, (2005)

More CK Information

- The standard treatment distance (x-ray target to point of deliver in tumor) is 80 cm. Although the CK does not have an isocenter, we use the 80 cm distance as a close approximation for the purpose of shielding calculations.
- The CK is calibrated (1 cGy/MU) at 80 cm.
- The IDR is 400 cGy/min at 80 cm.
- The leakage rate is < 0.1% at 100 cm.
- The machine has no flattening filter and uses circular cones, ranging in diameter from 0.5 to 6.0 cm.



Console area, controlled

B

d_B = 5.4 m

CyberKnife

Office, unctrl.

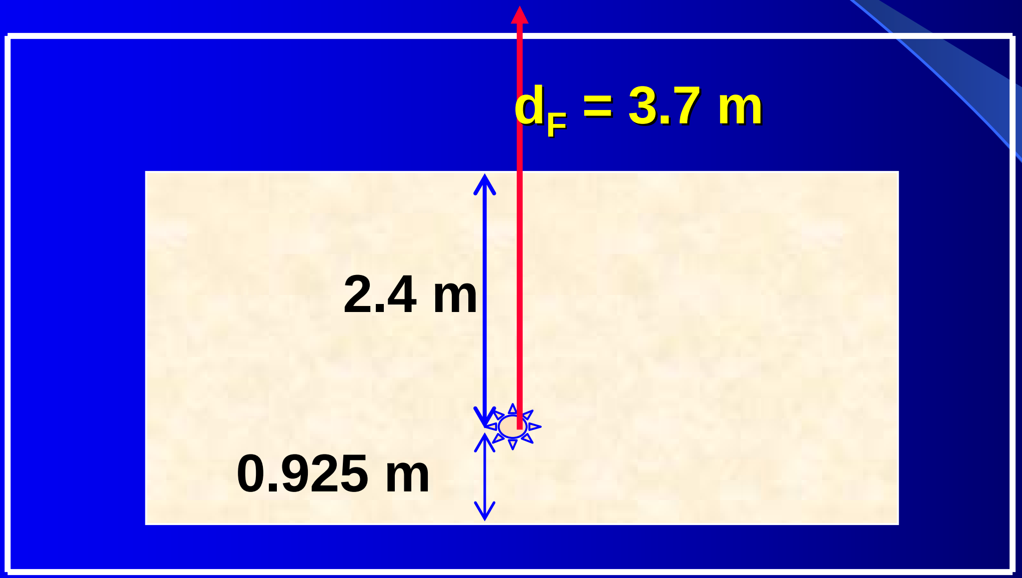
A

d_A= 4.3m

The Roof

F(unctrl, e.g. office)

or,   F'(ctrl)



d_F = 3.7 m

2.4 m

0.925 m

Shielding Calculations

Primary barrier: $P = B_{pri}\ W_{pri}(1m)\ U\ T\ /(d_{iso} + 0.8\ m)^2$

$W_{pri}(1m) = 0.8^2\ W_{pri}(0.8\ m) = 0.64\ (30\ TX/wk*12.5\ Gy/Tx)$

$= 240\ Gy/wk$ at 1 m

and d_{iso} = distance(m) from pseudo-isocenter to location

Leakage radiation ("secondary") barrier:

$P = B_L\ W_L\ T/(d_{iso})^2$

$W_L(1m) = C_l*W_{pri}(1m) = 15*240\ Gy/wk = 3600\ Gy/wk$

Patient scatter radiation is insignificant due to the small fields.

Calculation Results

Location	T	Ctrl/ Unctrl	n(pri)	n(L)	Combined n	Conc. x(cm)	Pb x(cm)
A	1	U	4.36	3.99	4.66	146	24.3
B	1	C	3.49	3.09	3.79	119	19.8
F	1	U	NA	4.12	4.12	129	21.5
F’	1/20	C	NA	2.12	2.12	65	11.0

TVL_1/TVL_e = 29.4 cm/31.9 cm (concrete), 4.8 cm/5.05 cm (Pb) [6.0 cm diameter field at 80 cm]

CK: IDR, R_w, and R_h Evaluations

Locat. (u/c)	IDR(pri) * μSv/min.	R_w^{pri} *T μSv/wk	R_w^{L}*T μSv/wk	R_w*T μSv/wk	R_h^{pri} ∇ μSv	R_h^{L} ∇ μSv	Combined R_h μSv
A(u)	2.1	10.0	4.2	14.2	0.5	0.2	0.7
B(c)	10.7	50.1	19.8	69.9	2.5	(1.0)	(3.5)
F(u)	NA	NA	20.	20	NA	1.0	1.0
F'(c)	NA	NA	100.	100.	NA	(100.)	(100.)

*** IDR(L) is < 0.015** μSv/min except at F', **1.4** μSv/min || ∇ **M = 1.5/0.75**

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