Site Planning and Design of PET/CT Facilities

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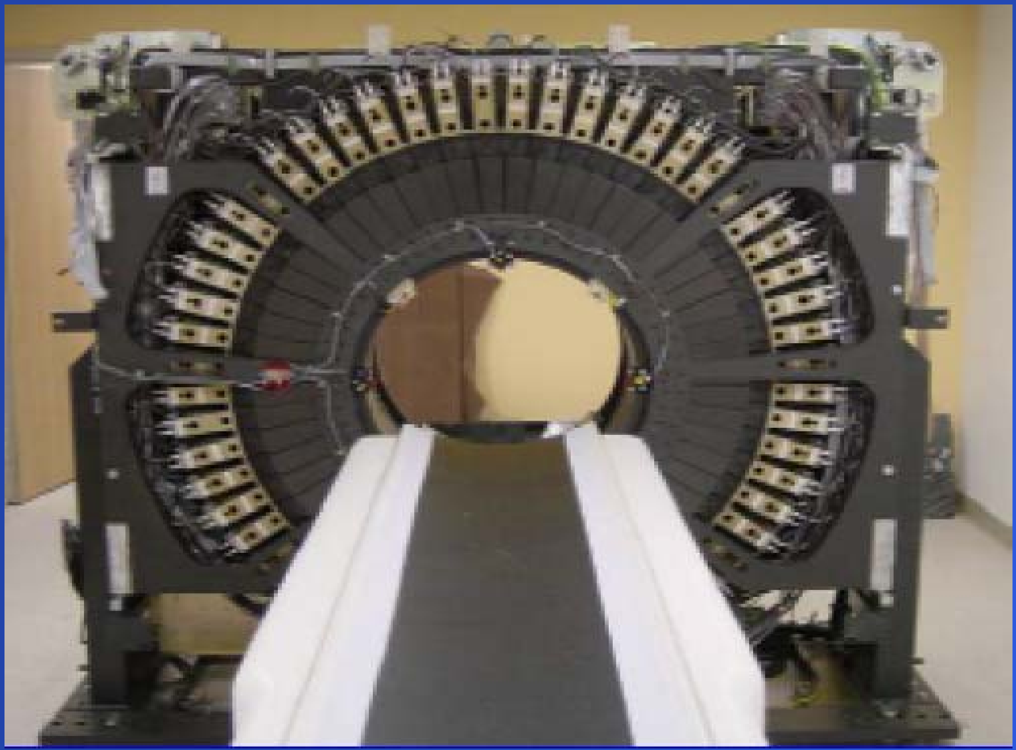
- AAPM Task Group #108 on PET and PET/CT Shielding Requirements

  Report published in Medical Physics 33:1, January 2006, pages 4-15 – Mark Madsen, Ph.D., Chair, University of Iowa Medical Center

- Jon Anderson, Ph.D. – UT Southwestern Medical Center, Dallas

GE Advance NXi



Site Planning and Radiation Safety

What Is Different When PET is brought into a department?

1) Requirements for patient handling during injection and uptake phase

2) 511 keV energy

-increases exposure rate from doses, patients

-greatly increases thickness of required shielding (hence, use time and distance when possible)

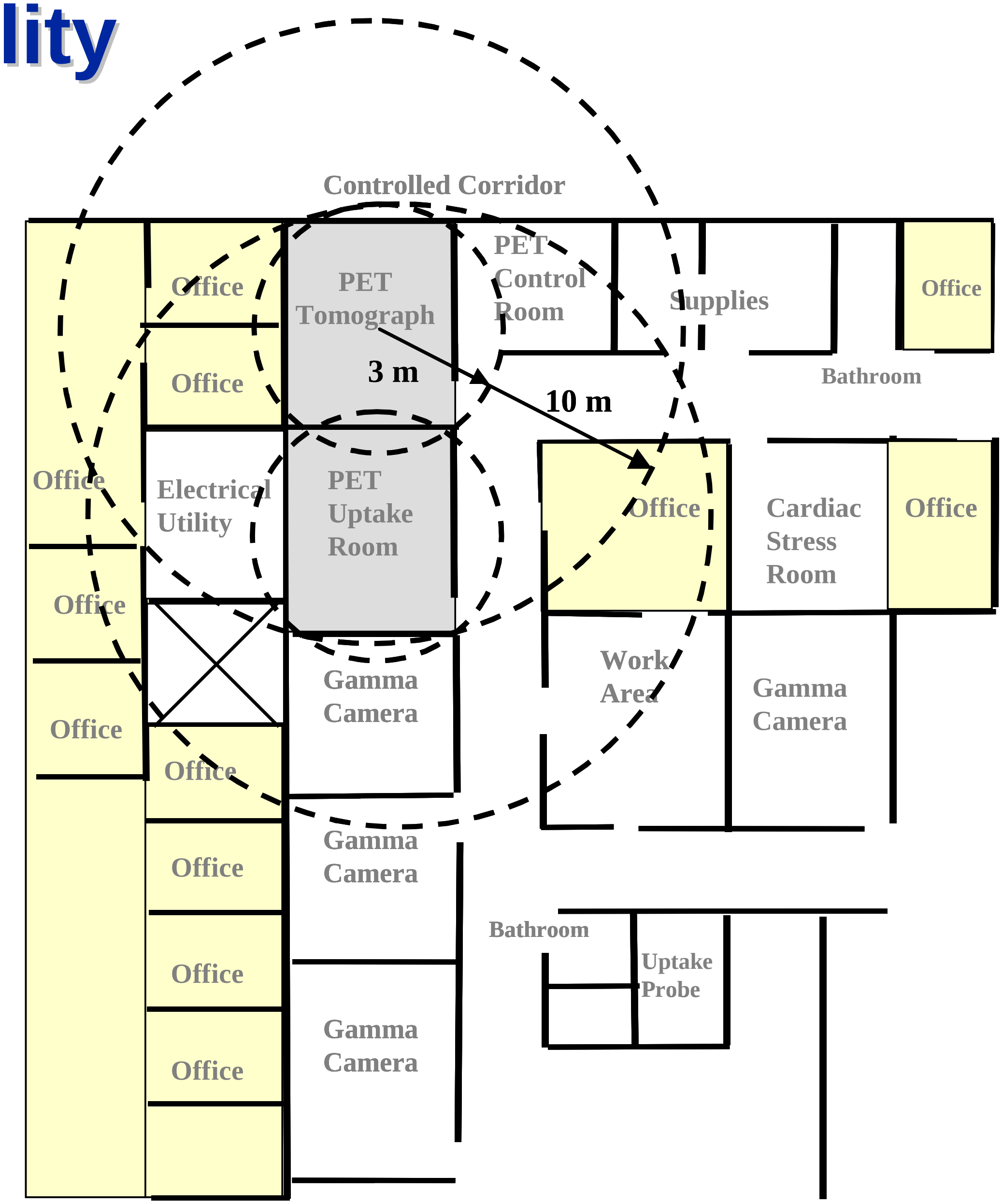
-each HVL is approximately 1/8 inch lead

3) Combined modality scanners (PET/CT) require consideration of both gamma-ray and x-ray hazard

Factors Affecting Radiation Protection

- Number of Patients Imaged
- Amount of Isotope Administered per Patient
- Length of Time each Patient Remains in the Facility
- Location of the Facility
- General Environs of the Facility

Typical PET Facility Room Layout



PET Exposure Factors: F-18

- **Half Life: 110 minutes**
- **Major Radiation Emission: 511 KeV Gammas**
- **Half-Value Layer: Several publications list 4.1 mm Pb and 3.4 cm for normal concrete for narrow beam conditions. Use of these values will *not* provide sufficient shielding since they neglect scatter buildup factors.**

  Tables of broad beam transmission for lead, concrete and steel based on Monte Carlo calculations performed by Doug Simpkin, Ph.D., are included in the AAPM task group #108 report on PET Shielding

Transmission Data for 511 keV photons [Douglas J. Simpkin, Ph.D.]

- **Curve fit to Archer Equation**

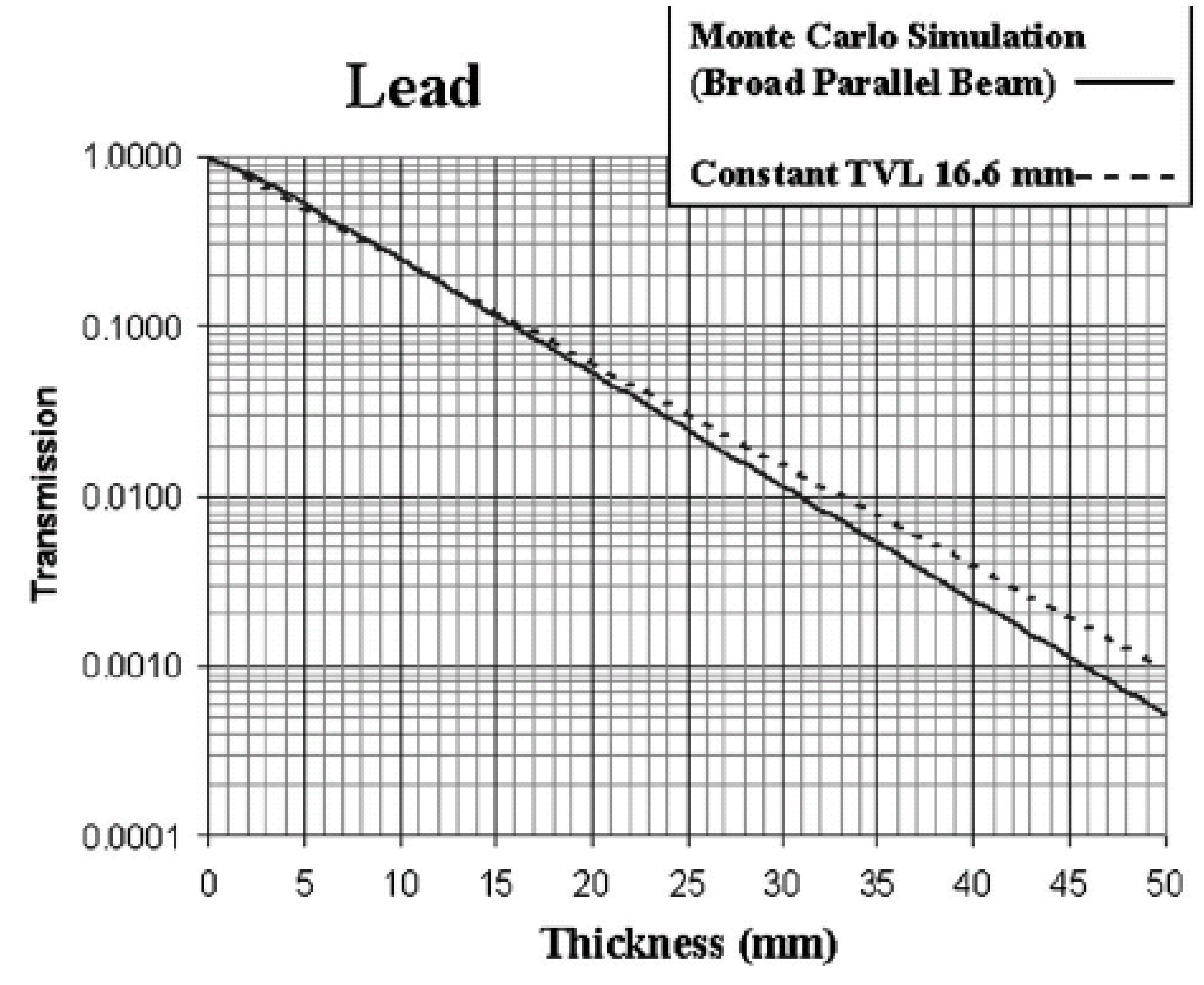
$$B = \left[\left(1 + \frac{\beta}{\alpha}\right) e^{\alpha \gamma x} - \frac{\beta}{\alpha}\right]^{-\frac{1}{\gamma}}$$

- **Calculated Constants**

Shielding Material	α (cm^{-1})	β (cm^{-1})	γ
Lead	1.7772	-0.5228	0.5457
Concrete	0.1539	-0.1161	2.0752
Steel	0.5704	-0.3063	0.6326

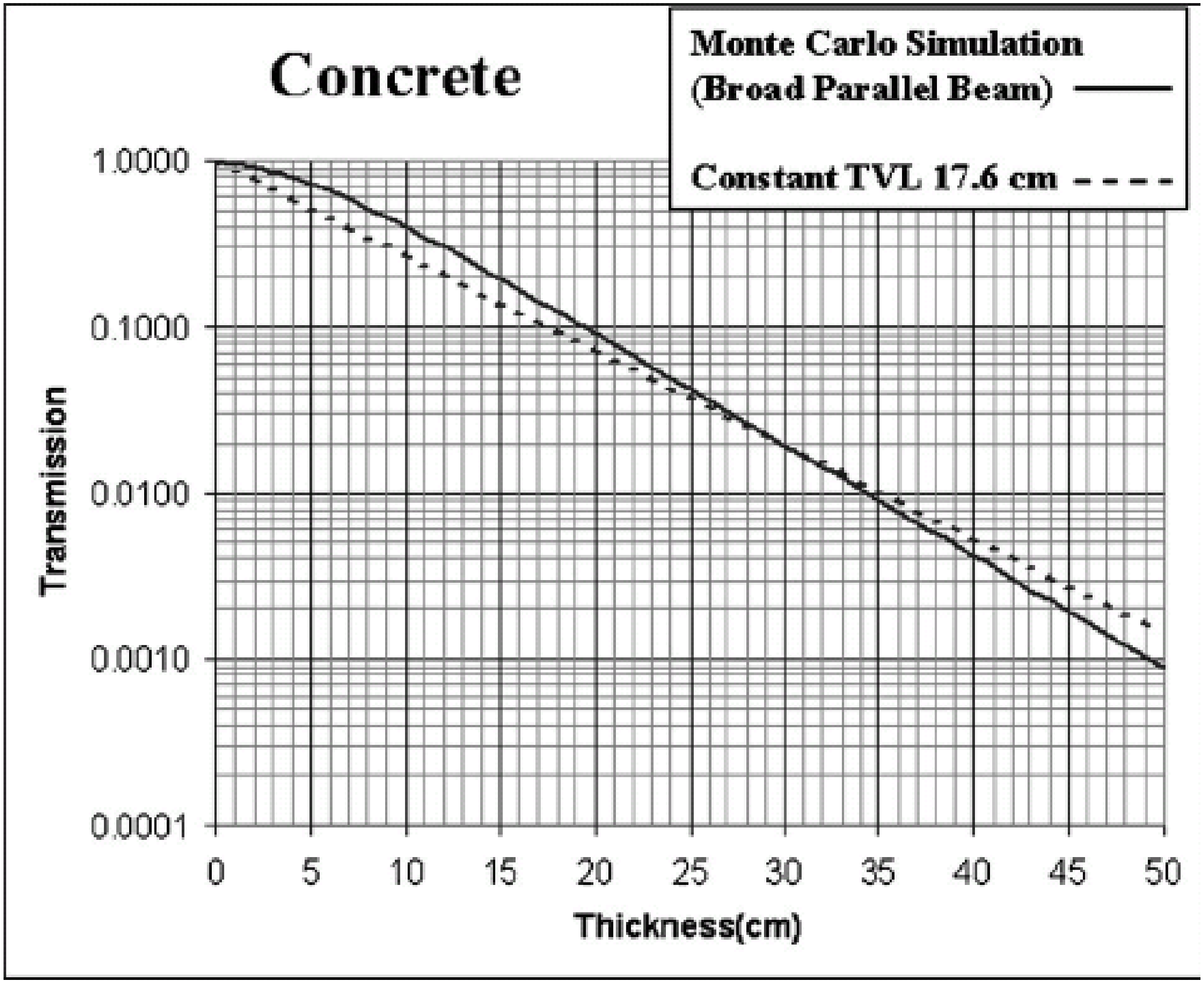
Transmission in Lead

- **Transmission is lower than constant TVL**



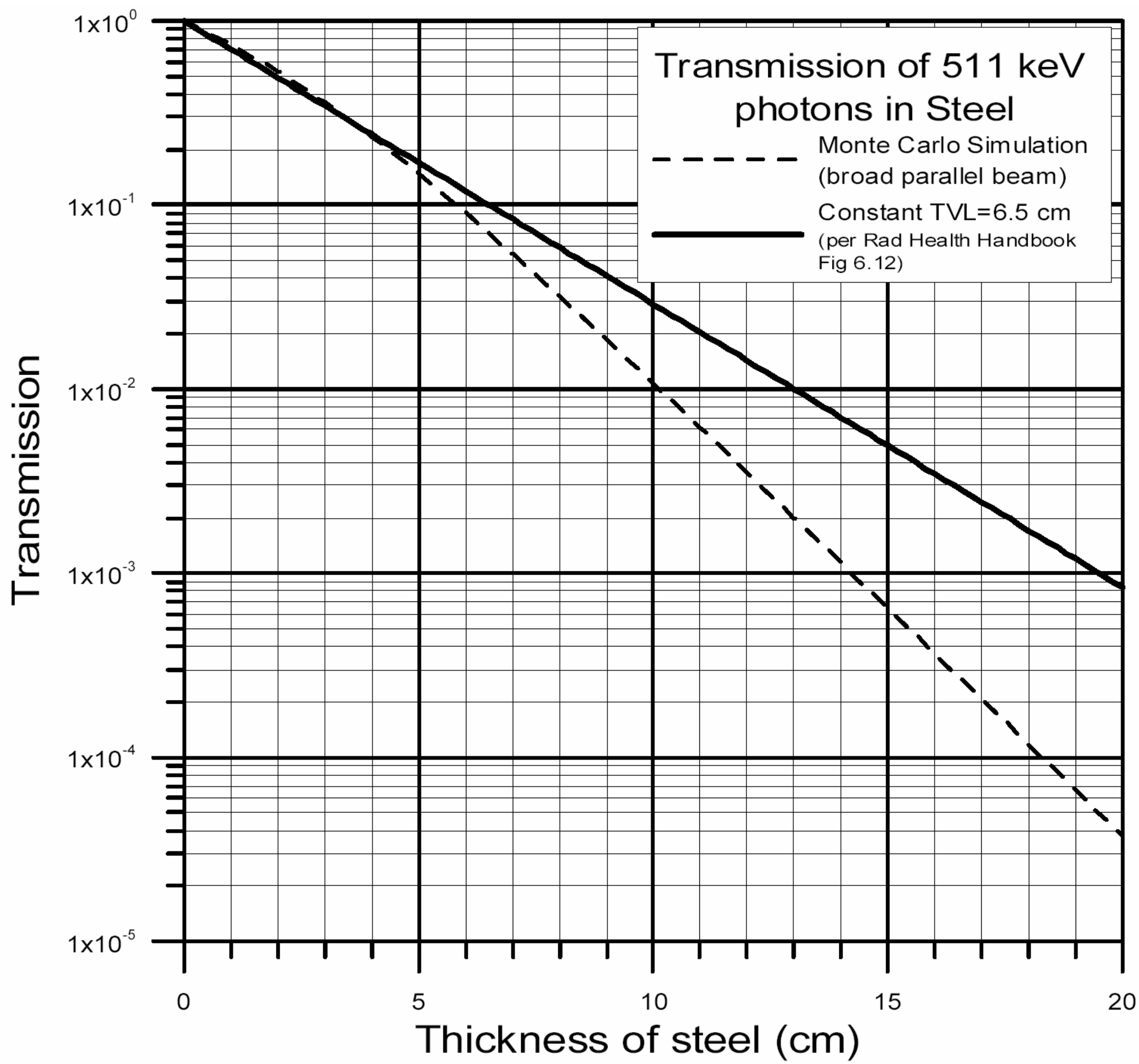
Transmission in Concrete

- Transmission is lower than constant TVL



Transmission in Steel

- Transmission is lower than constant TVL



Other PET Isotope Data

- N-13: Half life = 10 minutes
- O-15: Half life = 2.07 minutes
- C-11: Half life = 20.4 minutes
- Rb-82: Half life = 1.3 minutes
- Ga-68: Half life = 68.3 minutes
- These isotopes are dominated by the F-18 requirements

F-18 FDG PET Studies

- **F-18 FDG is a non-specific tracer for metabolic activity that is taken up normally in the brain, heart, bone marrow, bowel, kidneys and activated muscles, and concentrates in many metabolically active tumors.**
- **To reduce uptake in skeletal muscles, patients are kept in a quiet state after the administration of the F-18 FDG in either a bed or chair for 30-90 minutes depending on the type of scan and the practices of the institution.**
- ***The patient preparation room is a requirement for any PET facility and <u>must</u> be included in the radiation safety planning.***

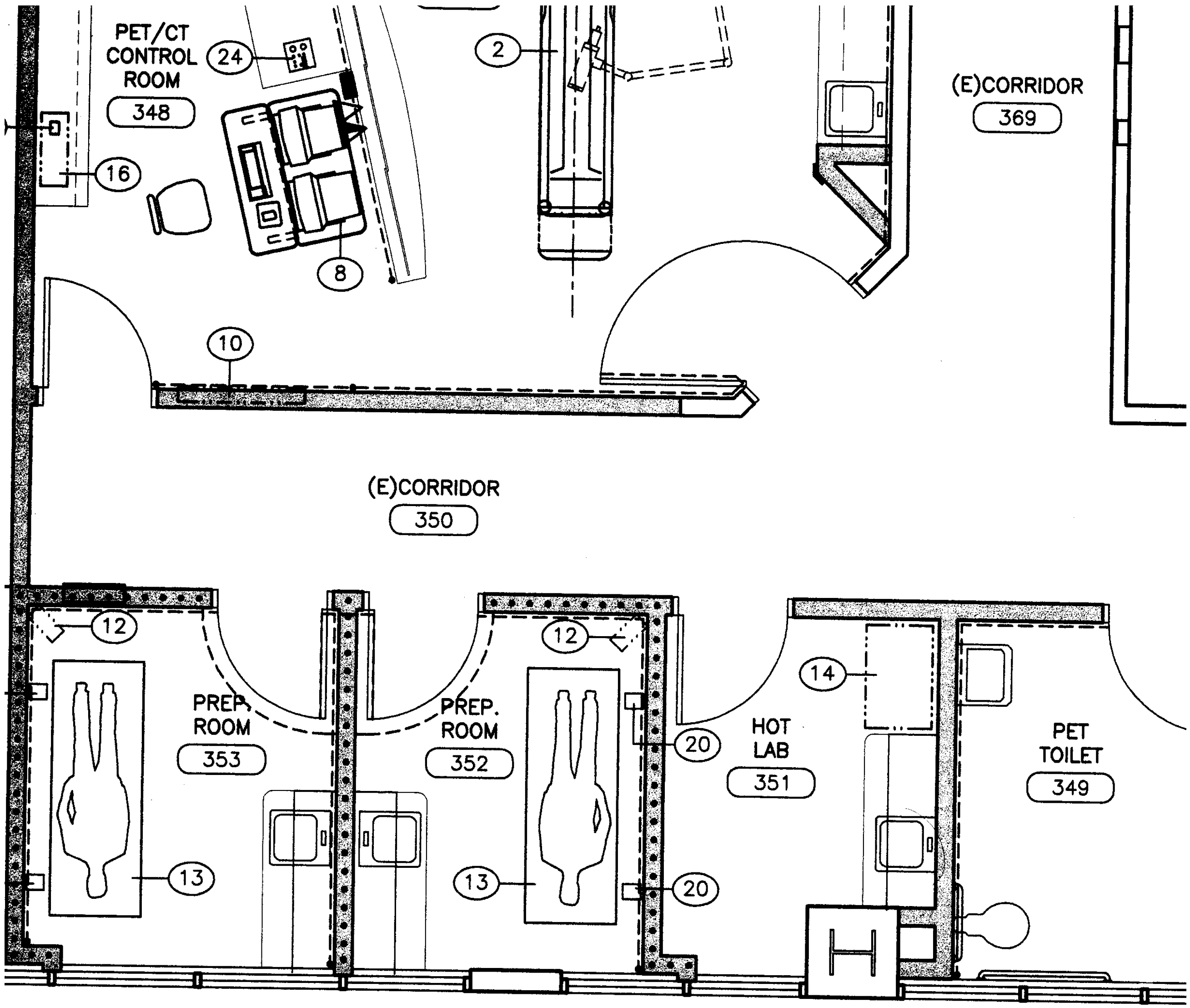
F-18 FDG PET Studies

- A busy PET facility will often have more than 1 patient in the uptake room. This must be considered when performing shielding calculations.
- Ideally, the busy PET facility will have more than 1 uptake room.
- After the uptake period, the patient should void to clear the radioactivity that has accumulated in the bladder which is <u>approximately 15%</u> of the administered activity
- It is highly recommended that a bathroom be reserved for PET patients

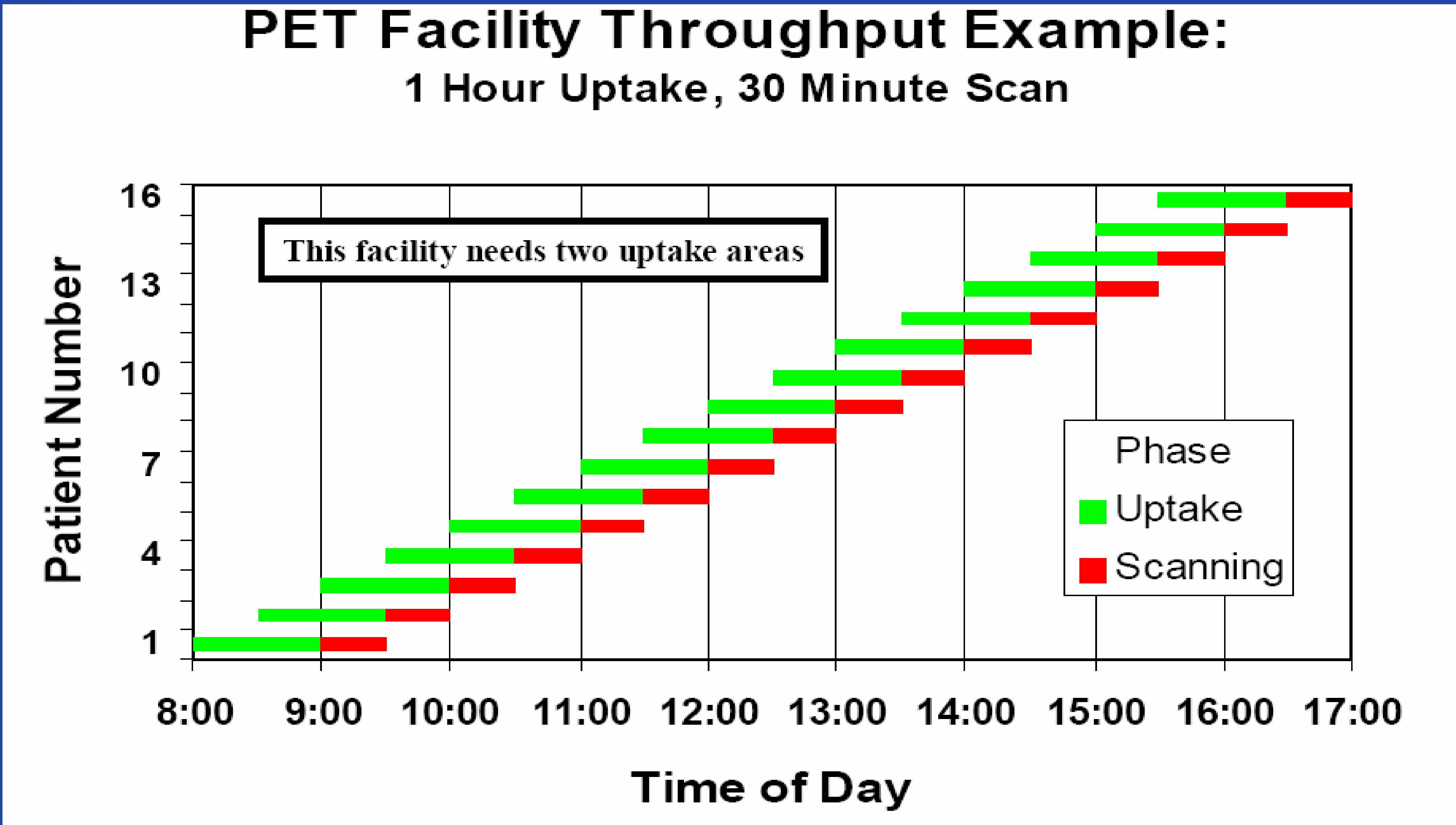
F-18 FDG PET Studies

- The patient is then positioned on the tomograph for the procedure and remains in the PET imaging room for 30-60 minutes
- Patients may be released immediately following the procedure or may go to a waiting area while the PET study is reviewed. If the patients are staying in the clinic for any significant length of time, radiation safety planning must be performed
- All areas in the vicinity of the PET imaging clinic must be considered for shielding calculations including the areas above and below the PET clinic as well as the adjacent areas on the same floor

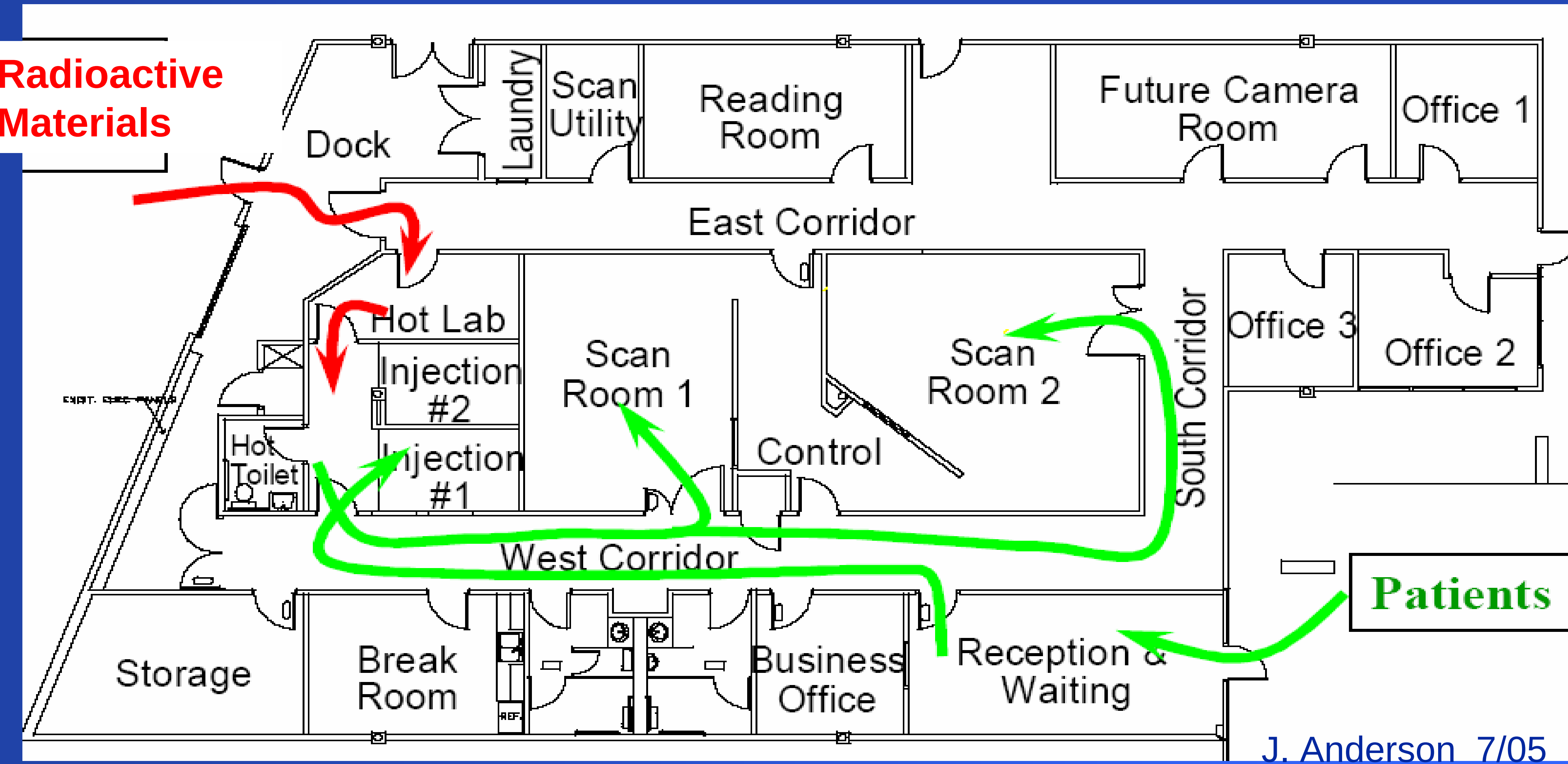
PET Prep Rooms/Toilet



Maximum Workload Estimation



PET Facility Layout Example



Hot Lab Details: Dose Assay and Preparation Area

Notes:

1) Calibrator convenient to dose storage
2) L Block close to calibrator
3) Note use of special PET carrier for syringe
4) Note L Block: thick window, 2" lead, 2" lead wrap-around

Injection/Holding Room Details

Injection/Holding Room Details

- 1) Injection/Holding room(s), Hot Lab, and PET/CT bays are most likely areas to need shielding
- 2) To minimize anomalous uptake

  -minimize external stimuli

  -keep patient quiet and still on gurney or in injection chair
- 3) Need adjacent hot toilet for patients to use after uptake period
- 4) Indirect lighting, curtains, noise control are desirable

F-18 Exposure and Dose Rate Constants

F-18 rate constants	Value	Units
Exposure rate constant	15.4	μR m^2/MBq h
Air kerma rate constant	0.134	μSv m^2/MBq h
Effective dose equivalent (ANS-1991)	0.143	μSv m^2/MBq h
Tissue dose constant[a]	0.148	μSv m^2/MBq h
Deep dose equivalent (ANS-1977)	0.183	μSv m^2/MBq h
Maximum dose (ANS-1977)	0.188	μSv m^2/MBq h

[a]Dose to 1 cm^3 of tissue in air.

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Information to Collect for Shielding Evaluation

- Uses of adjacent spaces (including above and below) and occupancy factors for them
- # patients/week
- Isotopes to be used, activity/pt
- Types of PET studies to be performed (Heads, Whole Body, Cardiac)
- Uptake time; scan time
- Dose delivery schedule; maximum activity on hand
- CT technique factors (kVp, mAs/scan, # scans per patient
- Amount of "non-PET" CT workload expected

PET Exposure Factors: F-18 FDG Studies

- For the AAPM Task Group Report, the following assumptions were made:
- Exposure Rate Constant: 0.57 mR m^2/mCi hr
  or 15.4 uR m^2/MBq hr
- Dose Rate Constant: 0.55 mrem m^2/mCi hr or
  when expressed as SI units: 0.143 uSv/MBq hr at 1 meter
- Workload for Scanner Room: 8-16 pts/day x 5 days/wk = 40-80 pts/wk
- Isotope Workload: Assume Patient is injected with 15 mCi (555 MBq) with an uptake time of 60 minutes
- Work week = 40 hrs/week

Radioactivity Administration-Dose Factors

- **Patient is the primary source of radiation that needs to be considered**
- **Since the body absorbs some of the annihilation radiation, <u>the dose rate from the patient is reduced by a factor of 2 or more</u>.**
  The mean maximum value reported at 1 meter from the patient just after administration is 3.0 uGy/hour/37MBq

Radioactivity Administration-Dose Factors

- Radioactive Decay: Because PET tracers have short half lives, the dose absorbed per hour is less than the product of the dose rate and the time. The total radiation dose received over a time period T,D(T), is less than the product of the dose rate and time by a factor of:

  $R_T = D(T)/(DR \times T) = 1.443 \times (T_{1/2}/T) \times (1\text{-}\exp(-0.693\ T/T_{1/2}))$

For F-18: this corresponds to factors of

30 minutes = 0.91

60 minutes = 0.85

90 minutes = 0.76

Shielding Design Goals

For shielding design guidelines, the following annual design goals are recommended:

General Public: 1 mSv/year

Occupationally exposed workers (as described by NCRP Report # 134): 5 mSv/year

In meeting these design goals, occupancy factors for low occupancy areas such as toilets or outdoor areas as described in current NCRP reports may be utilized.

Uptake Room Calculations

- Total dose at a point d meters from the patient during the uptake time (T_U) is

  3.0 uSv/hour/37MBq x A_0(MBq) x T_U (hours) x R_{TU}/d^2

If N_w patients are scanned per week, the total weekly dose is

3.0 uSv/hour/37MBq x A_0(MBq) x T_U(hrs) x R_{TU} x N_w/d^2

Uptake Room Calculations

For an uncontrolled area the NRC limit is 1 mSv/year corresponding to a weekly limit of 20uSv (2 mrem).

Therefore the barrier factor required is:

$$20 \text{ uSv}/3.0 \text{ uSv/hour}/37\text{MBq} \times A_0(\text{MBq}) \times T_U(\text{hrs}) \times R_T \times N_W/d^2$$

$$= 247\ d^2/(T_U(\text{hrs}) \times R_{TU} \times N_W \times A_0(\text{MBq}))$$

$$= 6.7\ d^2/(T_U(\text{hrs}) \times R_{TU} \times N_W \times A_0(\text{mCi}))$$

Uptake Room Calculations - Example

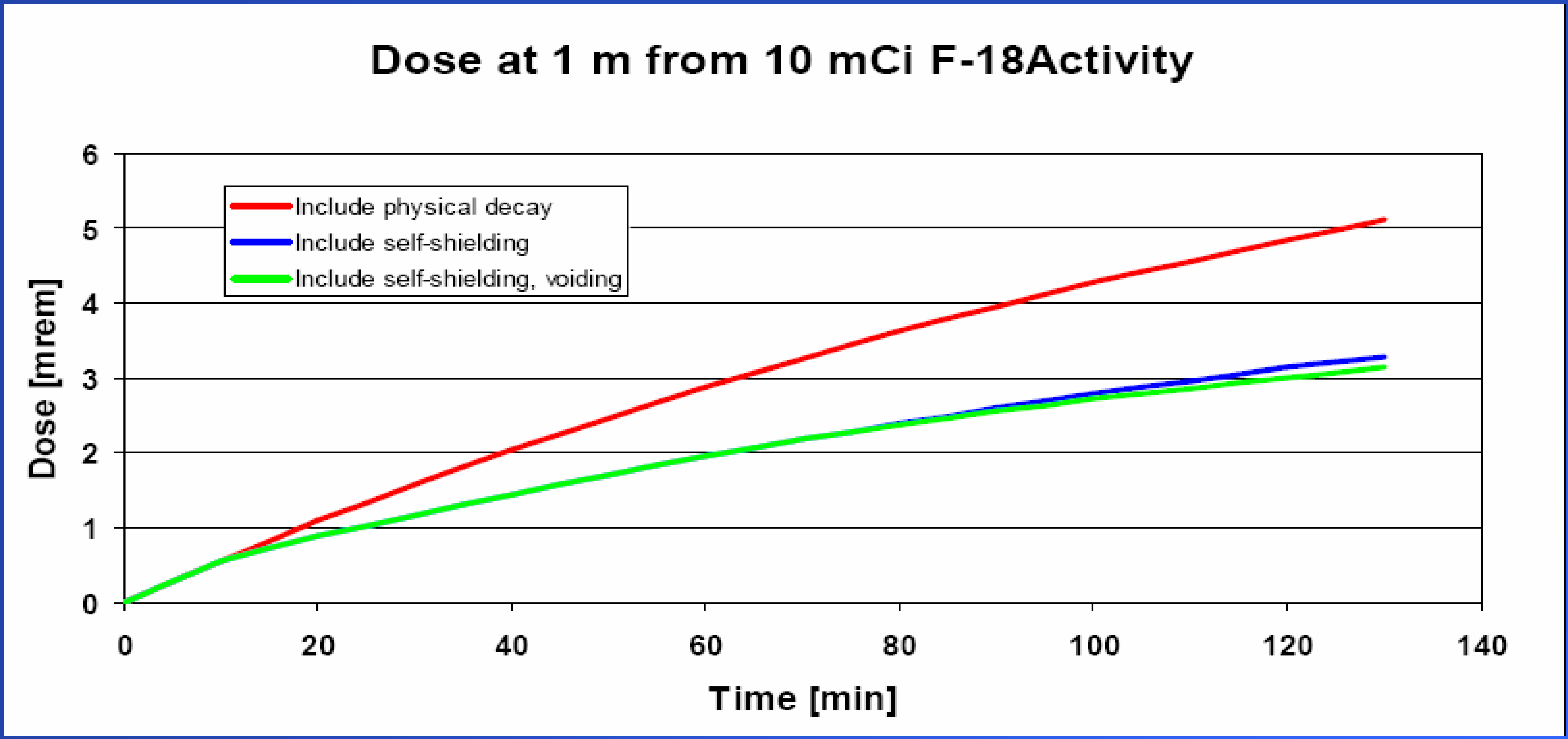
- What is the barrier factor required at a point 4 meters from the patient bed in an uptake room? Pt is administered 555 MBq (15 mCi) of F-18 FDG and there are 40 pts /week. Uptake time = 1 hour

Barrier Factor = $247\ (4)^2/(1 \times 0.85 \times 40 \times 555) = 0.21 = 2.45$ HVL

Using NCRP values, that requires 1.2 cm of lead or 13 cm of concrete

Using the Simpkin values, that requires 1.2 cm lead or 15 cm of concrete

Effects of Adding Corrections to Exposure Calculations



J. Anderson 7/05

Imaging Room Calculations

- **Most conservative approach is taken where no shielding from the tomograph is assumed. Method is then similar to that of the uptake area calculation. Because of the delay between the administration of the isotope and the actual imaging, the activity in the patient is decreased by**

  $F_U = \exp(-0.693 \times T_U(\text{min}) / 110)$ where T_U is the uptake time

In most cases, the patient will void prior to imaging removing approximately 15% of the administered activity

Imaging Room Calculations

- Barrier Factor =

  $3.0\ uSv/37\ MBq \times A_0\ (MBq) \times F_U \times T_I(hrs) \times R_{TI} \times N_w/d^2$

$= 247\ d^2/\ (N_W\ T_I(hrs) \times R_{TI} \times A_0(MBq) \times F_U$

For F^{18} at one hour, the decay factor $F_U = \exp(-0.693 \times 60/110) = 0.68$

The PET tomograph can provide a substantial reduction of the dose rate at some of the walls. This depends on the actual geometry and placement of the tomograph in the room.

Imaging Room Calculations – Example Calc

- What is the weekly dose equivalent to a point 4 meters from the patient during PET imaging. Patients are administered 555 MBq of F-18 FDG and there are 40 patients per week. The uptake time is 60 minutes and the imaging time is 1 hour.

Weekly dose equivalent = 3.0 uSv/37 MBq x 555 (MBq) exp(-0.693x60/110) x 40 x 1 x $0.85/4^2$ = 65 uSv

What is the barrier factor for occupancy of 1?

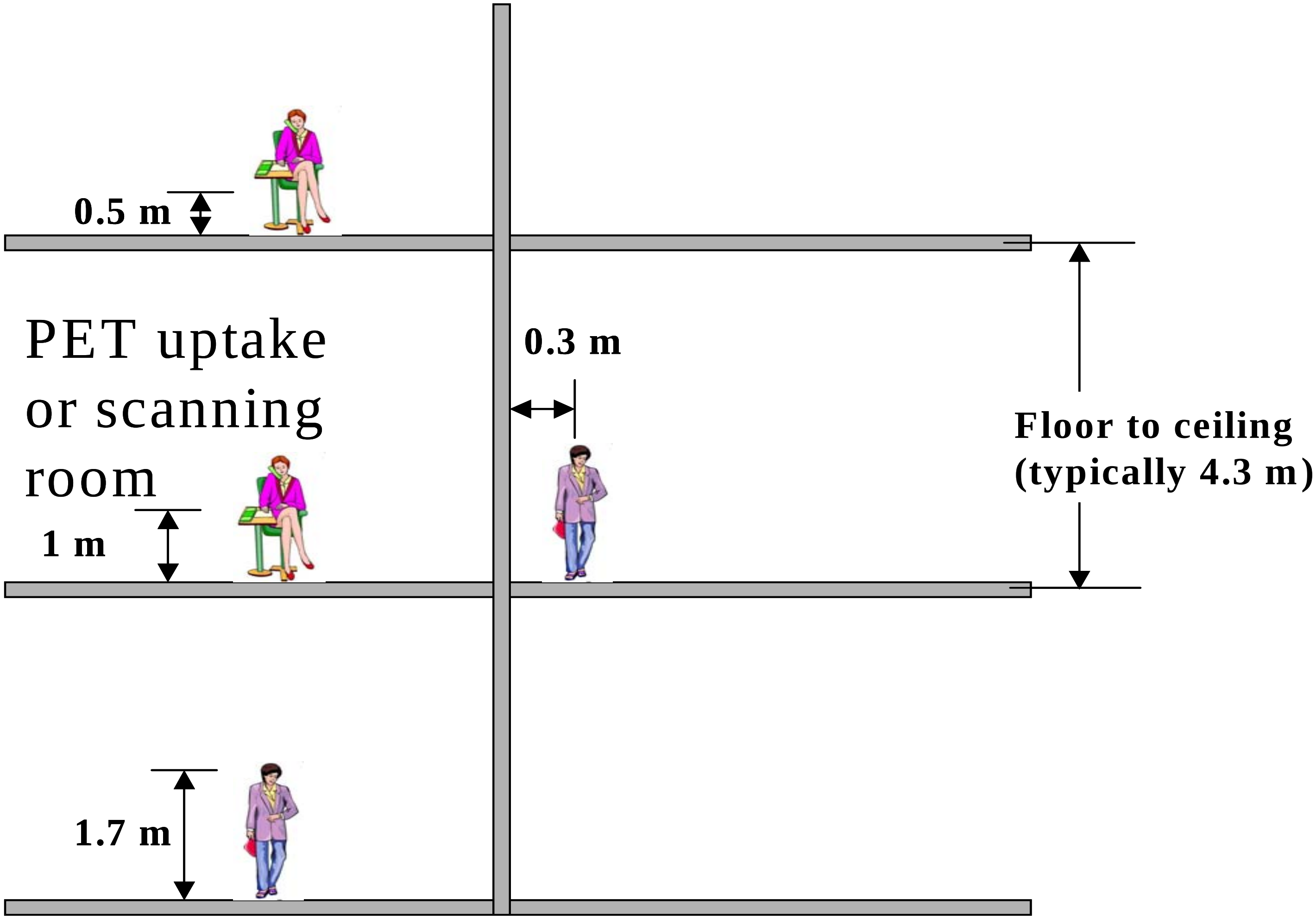
$247 \times 4^2 / (40 \times 555 \times 0.68 \times 1 \times 0.85) = 0.31$ = 1.9 HVL

- Using NCRP Values, this requires 0.95 cm of lead or 10 cm of concrete. Simpkin values require 0.95 cm of lead or 12 cm of concrete

Calculation for Rooms above and below the PET Facility

- Because the 511 keV annihilation radiation is so penetrating, it is necessary to consider uncontrolled areas above and below the PET facility as well as those adjacent on the same level. The following figure shows generally accepted source and target distances that apply in these cases.
- Typically, one assumes that the patient (source of the activity) is 1 meter above the floor. The dose rate is calculated at 0.5 meters above the floor for rooms above the source and at 1.7 meters above the floor for rooms below the source.

Distances to Be Used in Shielding Calculations



Distances to be used in shielding calculations

Calculation for Rooms above and below the PET Facility

- It should be kept in mind that it may be necessary to shield the vertical barriers all the way from the floor to the barrier above (instead of the 7 feet height usually required for x-ray installations).
- The vertical barrier need not have the same thickness over its entire height since the rays from the patient will traverse the higher portions of the vertical barrier obliquely and therefore pass through a greater thickness of shielding material.

Calculation for Room Above an Uptake Room - Example

- What is the weekly dose equivalent to a room above an uptake room? Patients are administered 555 MBq (15 mCi) of F-18 FDG, the uptake time is 1 hour and there are 40 patients per week. The floor to floor distance is 4.3 meters and there is 10 cm of concrete between floors.

D = (4.3 – 1) + 0.5 = 3.8 meters
Shielding factor for 10 cm of concrete is 2.5

$(3\ \text{uSv}/37\ \text{MBq} \times 555\ \text{MBq} \times 40 \times 1/3.8^2)/2.5 = 48.3\ \text{uSv/week}$

20 uSv/48.3 uSv = 0.41 = 1.3 HVL

Using NCRP values, this requires 0.65 cm of lead or 6.8 cm of concrete. Using Simpkin values requires 0.65 cm of lead or 9.3 cm concrete.

Dose Levels in Controlled Areas

- Dose levels in controlled areas are subject to ALARA considerations with the maximum limits set to 5 mSv per year.
- The technical staff that works directly with the PET patients receive the largest doses. Components of this dose include:

  Exposure from Patient Injections

  Exposure from Patient Positioning

  Exposure during Imaging

Adjacent Rooms on the Same Level

- Annual exposure to occupationally exposed individuals working in adjoining rooms (without shielding) is expected to be less than 5 mSv even for a busy PET tomograph.
- Using the values calculated in the earlier example, the weekly exposure rate at 4 meters from an uptake room that handles 40 patients per week with an average administered dose of 555 MBq (15 mCi) is 96 uSv or 5 mSv per year. This is the ALARA target of 5 mSv/year used by many clinics.
- It may be necessary to shield to a lower annual exposure level in some areas to compensate for the unavoidable exposure when personnel are close to patients.

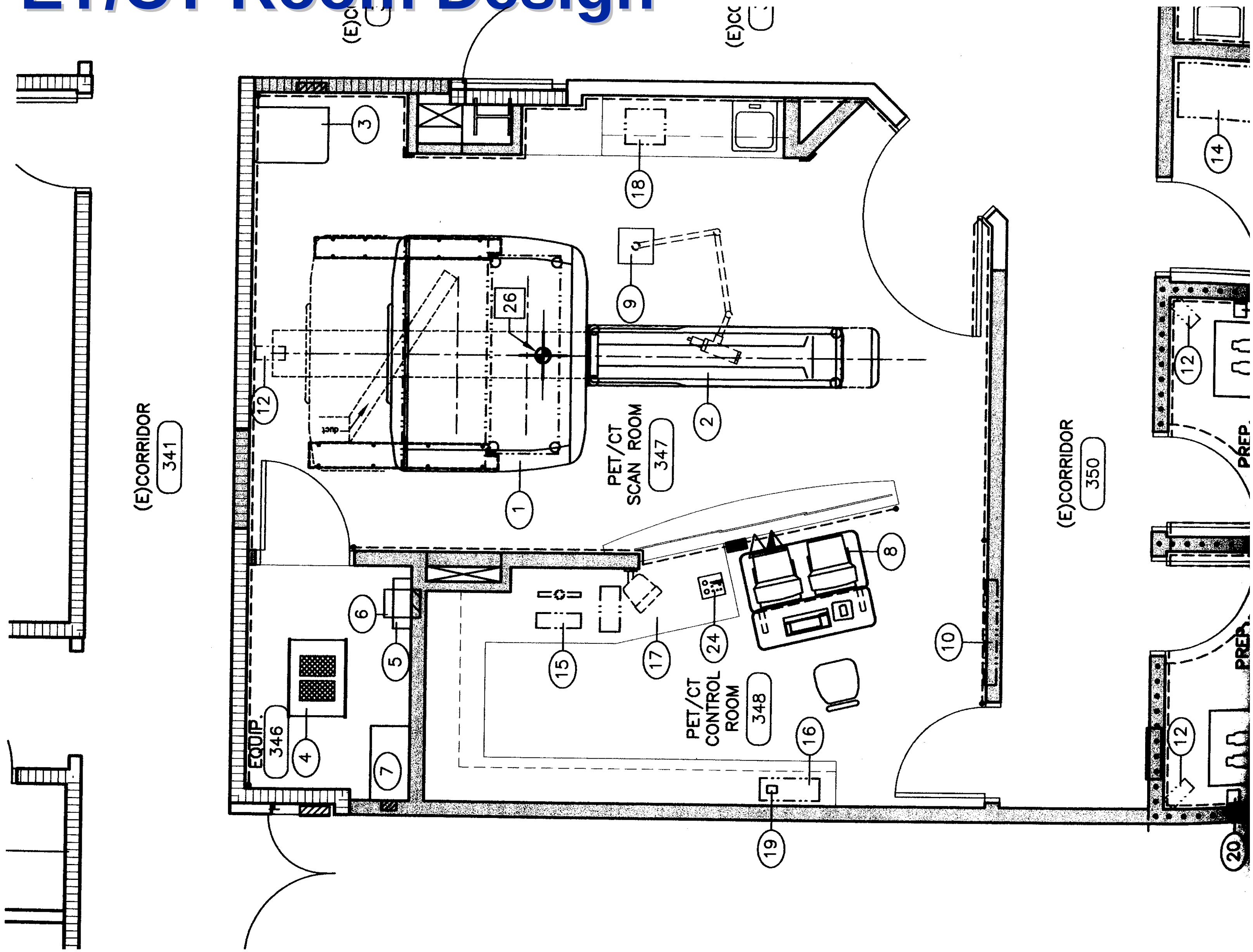
Design Considerations

- Additional shielding is recommended for the Nursing Stations and the PET/CT Control Room
- Uncontrolled areas with high occupancy should be located as far from the PET uptake and imaging rooms as possible
- If uncontrolled areas are located above or below the PET uptake and tomograph rooms, the spacing between floors may need to be greater than normal or additional shielding added. The floors need to be able to support the additional weight associated with additional shielding.
- Portable lead shields can be used effectively to shield patients in uptake rooms.

Design Considerations

- Floors and ceilings typically have 10 cm of concrete which amounts to about two half value layers
- Portable lead shields can be used effectively to shield patients in uptake rooms

PET/CT Room Design



PET/CT Installations

- Shielding for the CT portion of the PET/CT systems is substantially the same as for any CT installation
- If the PET/CT is used only in conjunction with PET imaging, the CT workload will be considerably less than that for a dedicated CT system
- Because the HVL for the CT techniques used is so much less than that for 511 keV photons, a room conservatively shielded for PET is unlikely to need additional shielding for the CT component

PET Shielding Calculations

Barrier	Distance 'D' (feet)	Unshielded Exposure at 'D' (mR/hr)	Occupancy Factor (T)	Unshielded Exposure at 'D' (mR/wk)	Maximum Permissible mR/wk	Required Shielding mm lead	in. lead
Control Room	12.0	0.43	1.00	17.13	10	2.80	0.11
Control Window	12.0	0.43	1.00	17.13	10	2.80	0.11
Toilet	9.0	0.76	0.25	7.61	2	6.95	0.27
Equipment	9.0	0.76	0.25	7.61	2	6.95	0.27
Corridor 341	8.5	0.85	0.25	8.54	2	7.54	0.30
Corridor 369	10.0	0.62	0.25	6.17	2	5.85	0.23
Door to Corridor	18.0	0.62	0.25	6.20	2	5.90	0.25
Prep Room 353							
Corridor	6.0	1.71	0.25	17.13	2	11.16	0.44
Door to Corridor	9.0	0.76	0.25	7.61	2	6.95	0.27
Hot Lab	4.0	3.86	1.00	154.20	10	14.21	0.56
PET Toilet Walls	8.0	0.96	0.25	9.64	2	8.17	0.32

Typical Shielding Requirements

- Walls will require 0.5 to 1.0 inch lead
- Doors will need 0.25 to 0.5 inches lead.   For door with lead > 0.25 inches, mechanical assist openers will be needed.
- Viewing window must be leaded glass or acrylic to match surrounding walls

Shielding of the PET Tomograph from Ambient Radiation

- The PET tomograph itself can be highly sensitive to ambient radiation, especially in the 3D mode
- Adjacent patient uptake rooms and other scan rooms must be considered.
- One PET vendor specifies a limit of 0.1 mR/hr for its unit
- This peak exposure rate shielding requirement may require more shielding than that needed just for personnel protection where the cumulative exposures are the concern

Conclusions

- PET requirements overwhelm any requirements of CT shielding in combination units
- Exposures to staff will be close to maximum permissible limits.
- Close monitoring of staff exposures will be needed.
- Shielding will be typically at least 0.5 inches of lead in the walls with 0.25 to 0.5 inches in the door.
- Shielding will probably be needed on the ceilings or floors for facilities with occupied areas above or below these rooms

Conclusions

A Qualified Medical Physicist MUST be involved in the design of the shielding for a PET/CT suite.

Following installation, a Qualified Medical Physicist should determine the adequacy of the shielding.

A Qualified Medical Physicist should specify and review the Quality Assurance Program for the PET and PET/CT

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