Considerations for the Shielding of Nuclear Medicine and PET Facilities

Richard E. Wendt III

Department of Imaging Physics
The University of Texas MD Anderson Cancer Center

rwendt@mdanderson.org

SAMs participants might want to take particular note of the slides with the picture of Samuel Goudsmit, a famous physicist named Sam:

According to the IAEA

"It is convenient to shield the source, where possible, rather than the room or the person. Structural shielding is in general not necessary for most of the areas of a nuclear medicine department. However, the need for wall shielding should be assessed, for example in the design of a therapy ward (to protect other patients and staff) and in the design of rooms housing sensitive instruments (to keep a low background in, for example, well counters and gamma cameras)."

My first experience in Nuclear Medicine, forty years ago, was in a clinic that had six cameras in a large, open room. These cameras typically looked either up or down and thus did not suffer from much cross-talk. The only SPECT camera was off in a separate area. In more spatially confined labs with higher workloads, the likelihood of needing structural shielding goes up. That is further affected by the growth of hybrid imaging. With the exception of a portable gamma camera for bedside imaging, all of our gamma cameras are SPECT/CT cameras and thus shielding is required for the CT component as well as for the radionuclides. Positron emission tomography uses higher energy photons and therapeutic nuclear medicine uses higher activity levels that often necessitate structural shielding.

Time, Distance and Shielding

- Time
  - Sources are always on.
- Distance
  - Space is often at a premium, and its use may be decided without consulting the qualified medical physicist.
  - A location might be irradiated from all sides by different sources.
- Shielding
  - Localized shielding works for sealed sources, "doses" and some forms of waste.
  - Structural shielding might be necessary for the patients as sources.

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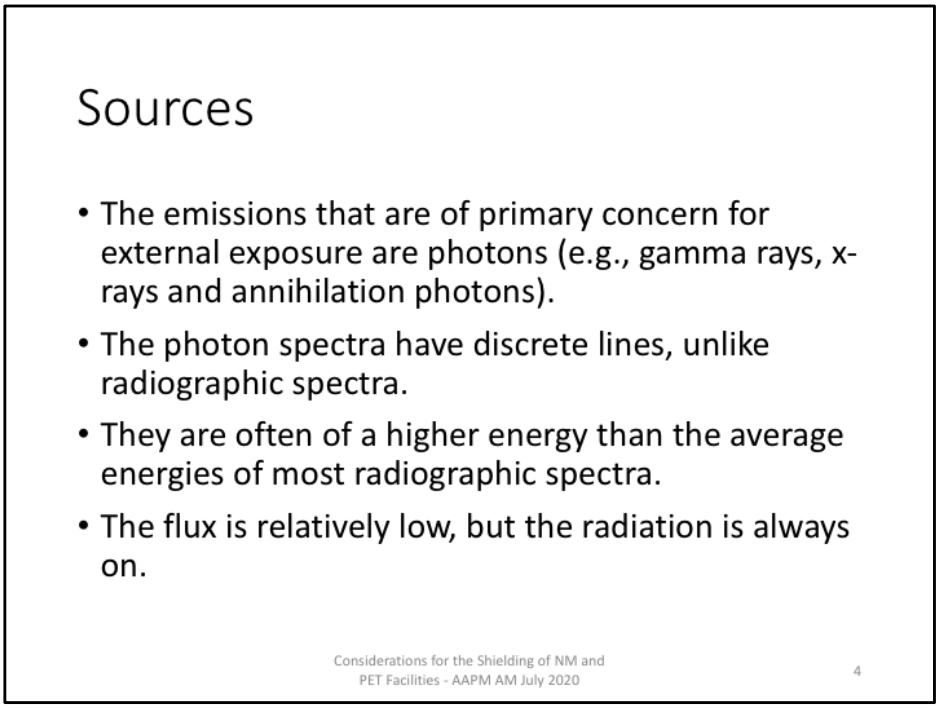
Of the three watchwords of radiation protection, time is important because radioactive sources are always on. Distance is very effective, thanks to the inverse square law, but space is often at a premium in modern clinics, and a location might well be irradiated by a number of sources at different spots in the clinic. Shielding can be localized such as pigs, transport cases and shielded cabinets. However, patients cannot practically be shielded by most localized means, and so structural shielding is necessary.



The dose imparted by penetrating radiation is the dominant concern when designing shielding. Radionuclides typically have relatively discrete photon spectra unlike continuous radiographic spectra. Most radionuclides in nuclear medicine have higher energy gamma rays than the average energy of the typical diagnostic X-ray spectrum. While the flux from radionuclides is lower than that from X-ray machines, the radiation is continuous.

Radionuclides

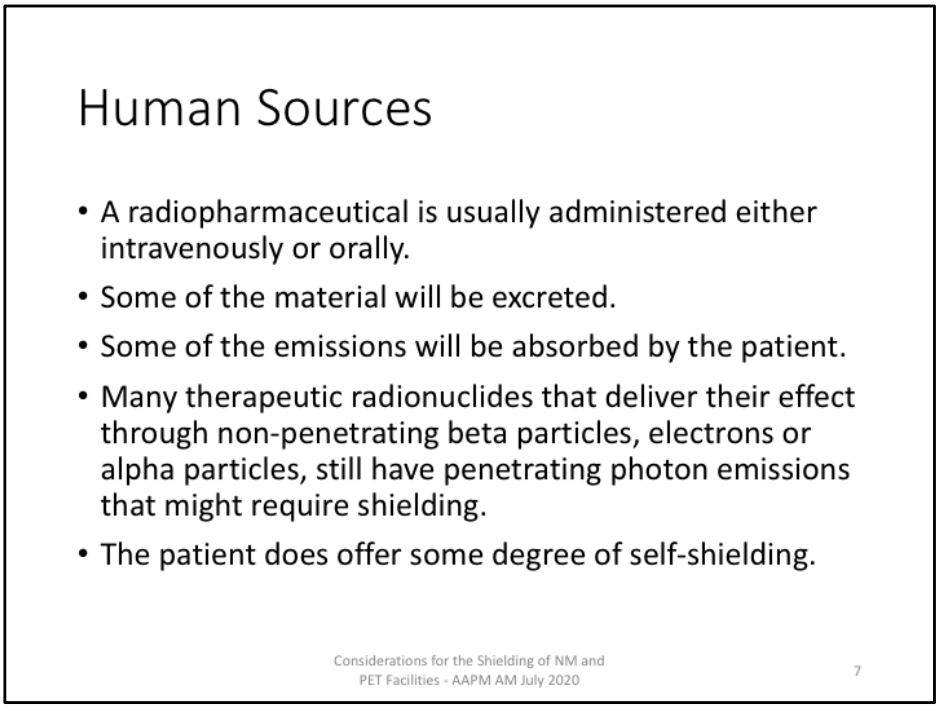
- So-called pure beta emitters such as P-32 and Y-90 do create a slight amount of bremsstrahlung radiation, but as Zanzonico's estimated dose rate constants demonstrate, the bremsstrahlung poses no appreciable hazard.
- Some of the alpha emitters, such as Ra-223 do have some photon emissions, but at the low activities that are administered, those are negligible from a safety standpoint.

Even the pure beta emitters produce some bremsstrahlung but Pat Zanzonico has shown that the dose rate from that bremsstrahlung is very modest. The administered activities of the alpha emitters are typically so low that their penetrating emissions pose no safety concerns.

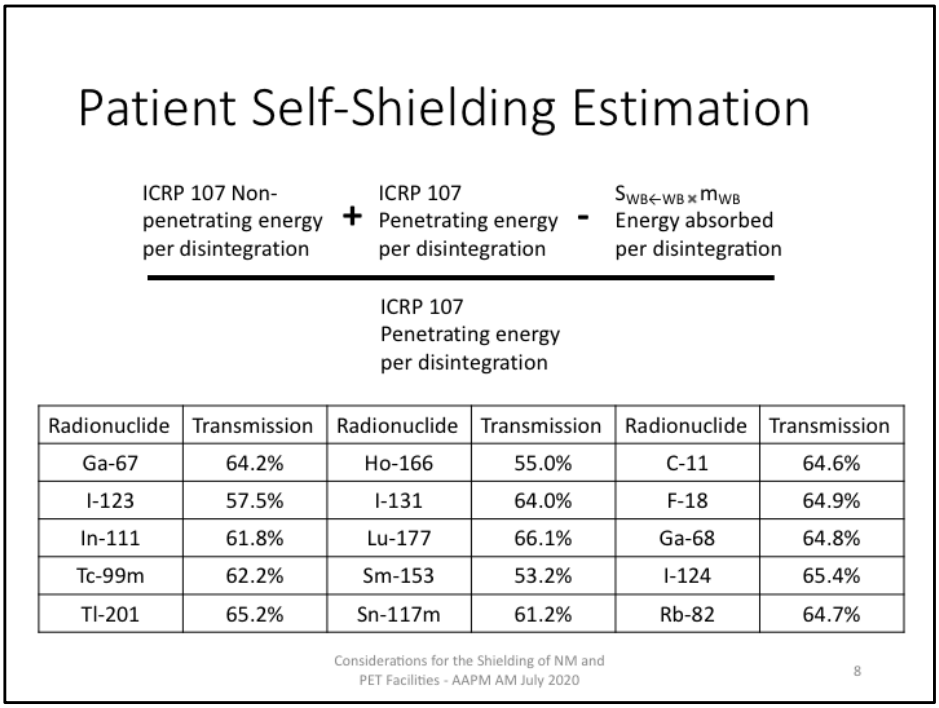
Radionuclides

- A number of the therapeutic radionuclides, such as I-131, In-111, Lu-177, Ho-166, Sm-153 and Sn-117m, have appreciable photon emissions that typically must be shielded at therapeutic activities.
- There are many diagnostic radionuclides, among them Tc-99m, I-123, I-131, In-111, Ga-67, Tl-201, Xe-133, F-18, Rb-82, O-15, N-13, Y-86, Zr-89 and I-124, that might require shielding even for diagnostic administered activities if the clinical workload is high enough or the clinic is so confined that it cannot exploit time and distance alone.

Most of the therapeutics radionuclides, by count if not by frequency of administration, have penetrating emissions that are strong enough at therapeutic activities to warrant at least the consideration of shielding. The two most popular right now are I-131 and Lu-177. We have a suite of four I-131 outpatient therapy rooms that have half an inch of lead in the walls, floor and ceiling. The diagnostic radionuclides, many of which are listed here, might require shielding depending upon the workload in the clinic and the spaciousness of its layout. All but the most spacious PET facility will almost certainly need some structural shielding.

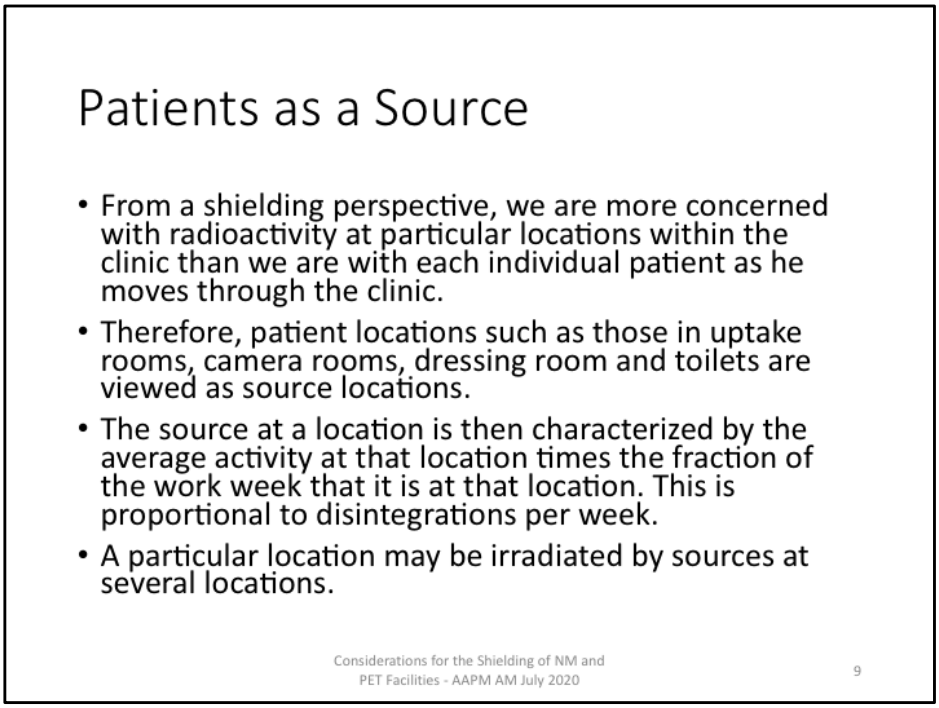


Patients, research subjects and in some situations preclinical research subjects internalize radionuclides through various routes of administration. Typically, physical decay is augmented by biological clearance mechanisms. The patient himself will absorb essentially all of the nonpenetrating emissions and typically a non-negligible amount of the penetrating emissions. A fair number of the commonly used therapeutic radionuclides emit penetrating radiation to some extent. Patents absorb some of these emissions and offer a degree of self-shielding.

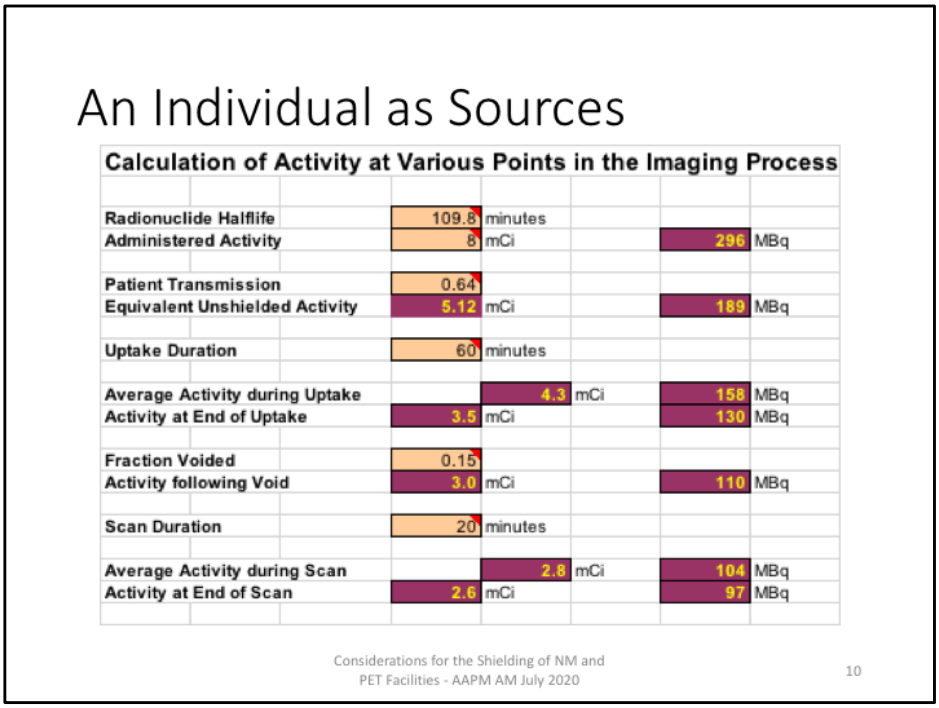


Radionuclide	Transmission	Radionuclide	Transmission	Radionuclide	Transmission
Ga-67	64.2%	Ho-166	55.0%	C-11	64.6%
I-123	57.5%	I-131	64.0%	F-18	64.9%
In-111	61.8%	Lu-177	66.1%	Ga-68	64.8%
Tc-99m	62.2%	Sm-153	53.2%	I-124	65.4%
Tl-201	65.2%	Sn-117m	61.2%	Rb-82	64.7%

There is a straightforward way to estimate the self-shielding of the patient. The whole-body S-value from the MIRD schema times the whole-body mass gives the energy per disintegration that is absorbed in the whole body. ICRP 107 gives the energy per disintegration from non-penetrating radiation and that from penetrating radiation. The difference, divided by the penetrating energy per disintegration is the fraction that is transmitted from the whole body. It ranges from 53 to 66% for a collection of more common radionuclides. In a cohort of 200 I-131 patients with external exposure rate readings, we calculated an average transmission factor of 59%, which is reasonably close to the 64% that is given by this method. I regret that I have forgotten who first developed this approach and thus cannot give proper credit to its author.



When designing structural shielding, we are working with averages over periods such as the work week. On that time scale, what matters is the amount of radioactivity at particular locations, not the perambulations of an individual patient through the department. We consider source locations including uptake rooms, dressing rooms, toilets, camera rooms and sometimes even waiting rooms. We work with the average activity while the source is present and the fraction of the work week that it is present, which is proportional to disintegrations per week.



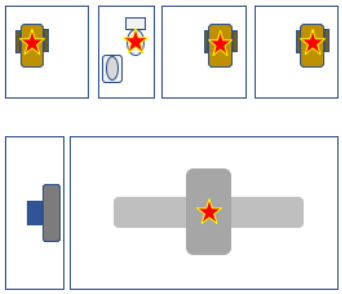
Here is an example in which we give a patient 8 mCi of F-18 FDG. The patient transmits 64% of the penetrating radiation, so the equivalent activity in air is 5.12 mCi. With a 60 minute uptake time, the equivalent activity in air will have decayed to 3.5 mCi. The average equivalent activity in air in the uptake room was 4.3 mCi. Patients void 15% of the administered activity of F-18 FDG, so after the patient's urinating, the equivalent activity in air that enters the scanner room is 3.0 mCi and the average equivalent activity in air during the 20 minute long scan is 2.8 mCi.

Patients as Sources at Locations

Sources

Activity Converter:	4.3	mCi =	159.1	MBq

ID	Location	Nuclide	Avg. Activity	Workfactor	MBq-hr/wk	uSv-m^2/wk @ 1m	Comment
S1	Uptake Room 1	F-18	158.1	0.66666667	4216.00	623.893	80 pts/wk * 1 hr / 3 rooms
S2	Uptake Room 2	F-18	158.1	0.66666667	4216.00	623.893	80 pts/wk * 1 hr / 3 rooms
S3	Uptake Room 3	F-18	158.1	0.66666667	4216.00	623.893	80 pts/wk * 1 hr / 3 rooms
S4	Toilet	F-18	130.0	0.16666667	866.67	128.251	80 pts/wk * 5 min
S5	PET Scanner	F-18	104.0	0.66666667	2773.33	410.404	80 pts/wk * 20 min



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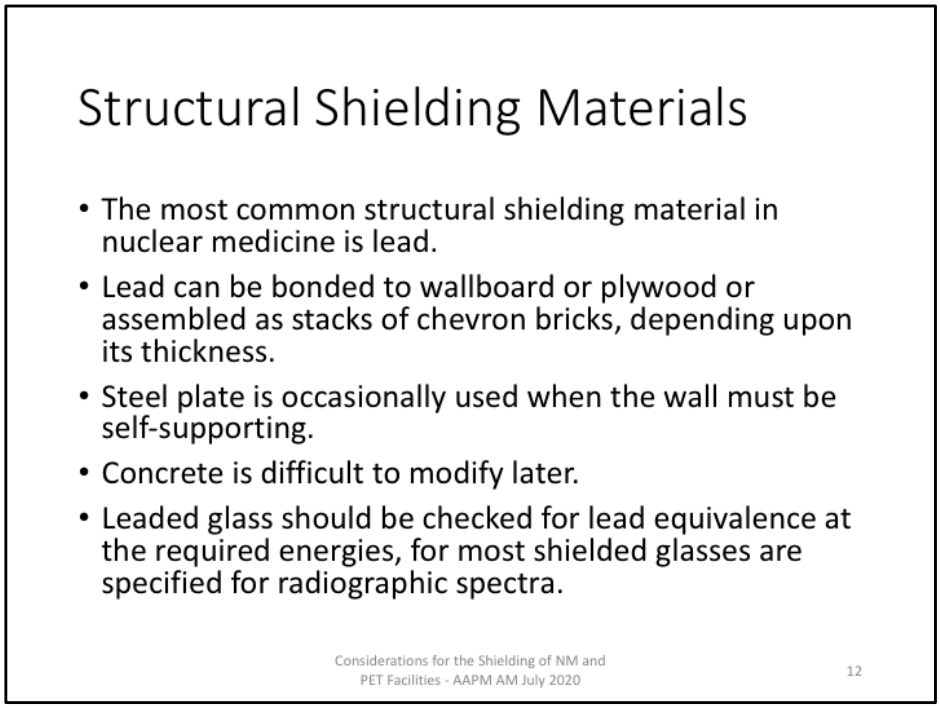
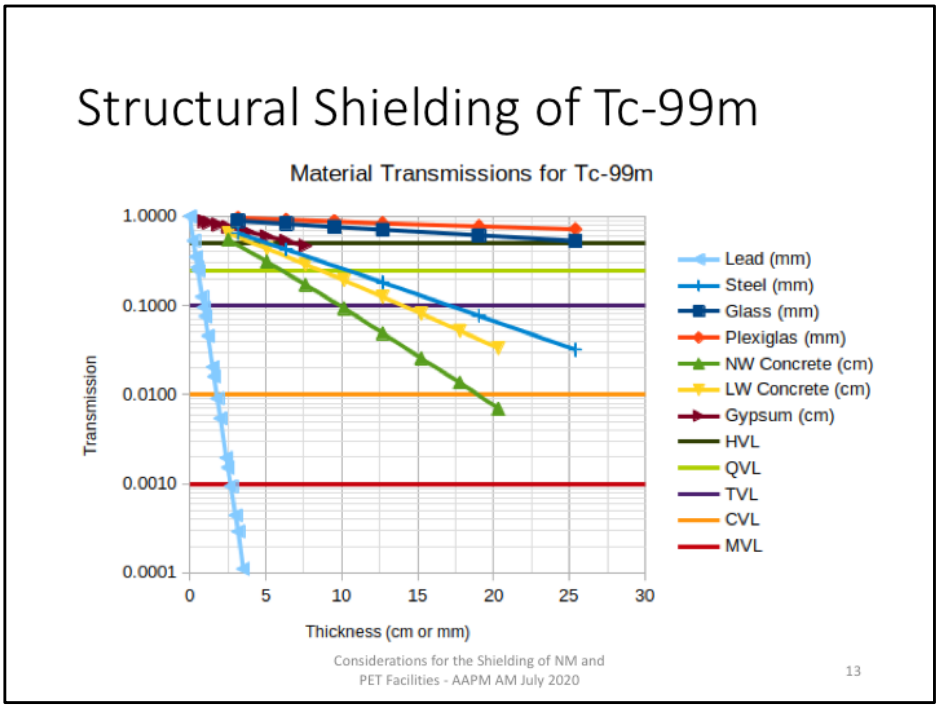
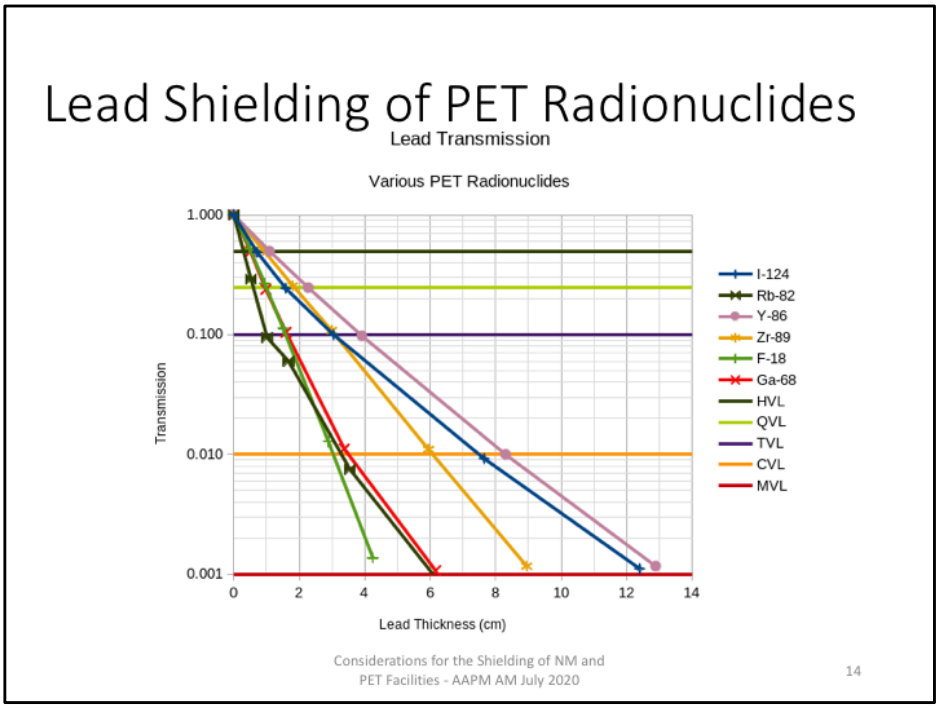
Now, if we consider the various locations that contain radioactivity in this example, we determine the average equivalent activity in air at each of those location and the fraction of the work week that it is present (here called the workfactor). From that we get what amounts to the disintegrations per week and, using the dose rate constant of a source in air, the weekly dose rate from each source location.



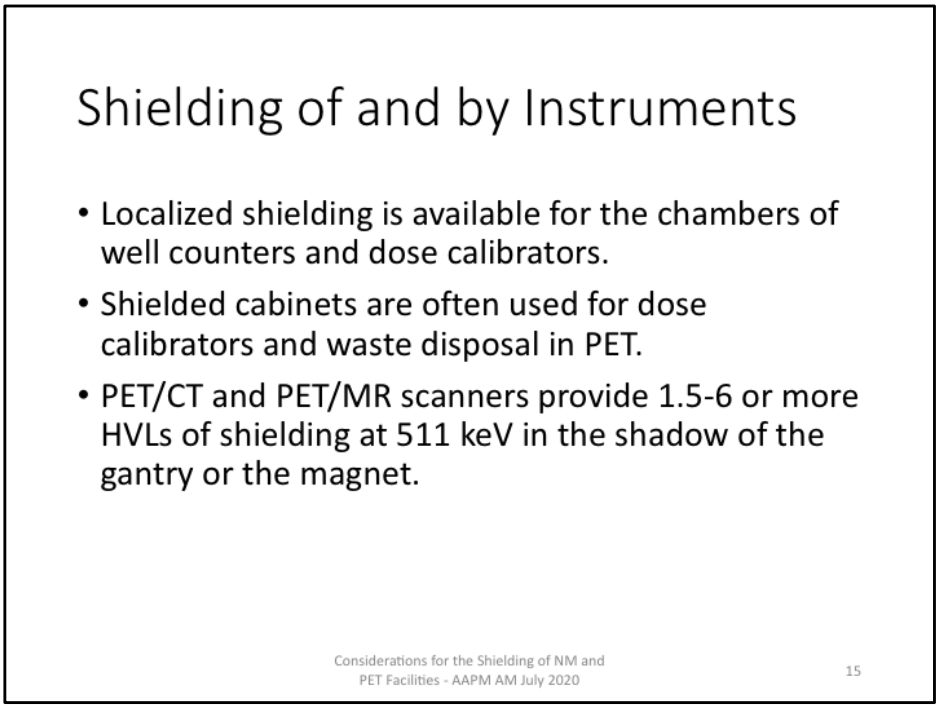
There are a number of different materials that may be used for structural shielding. Lead is probably the most common because of its familiarity and versatility. It can be bonded to gypsum wallboard or to plywood. We have seen steel plates and concrete used in very specific circumstances where lead was not practical such as a cyclotron vault and in in-patient therapy rooms. The lead equivalence of leaded window glazing might be correct only for radiographic energies and might need to be derated for the higher energies of radionuclide emissions.



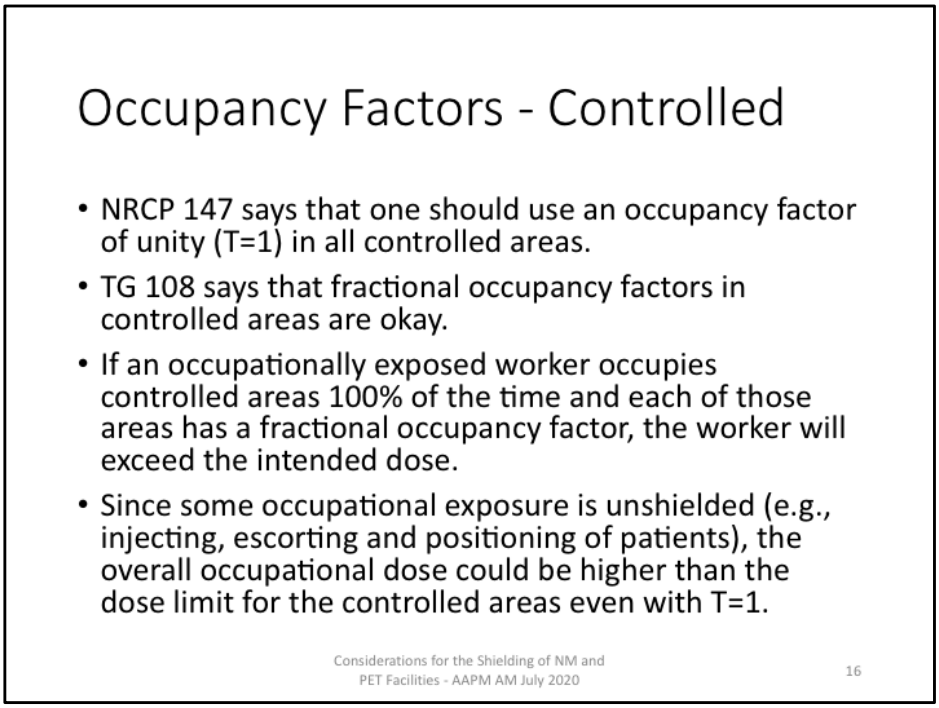
These are Monte Carlo simulations of the deep dose equivalent of a point source of Tc-99m spectrally shaped by 1 cm of tissue for a number of different shielding materials. The horizontal axis is thickness, which is in mm for some materials and cm for other materials. HVL, QVL, TVL, CVL and MVL are shown as horizontal lines. Lead, in light blue is clearly the most efficient. Steel, in medium blue, has a modest, but still appreciable effect. Plate glass and Plexiglas offer less than one HVL even at an inch's thickness. It takes more than two inches of gypsum wallboard to achieve 1 HVL. Lightweight and normal weight concrete are somewhat more effective, and the thicknesses that are found in typical construction might offer as much as a TVL of shielding.



These are simulations of the attenuation by lead of a number of PET radionuclides. The horizontal axis is the thickness of the lead in cm and the vertical axis is the transmission factor. HVL, QVL, TVL, CVL and MVL are shown as horizontal lines. F-18 in green has a half value layer of slightly more than 5 mm and a quarter value layer of slight less than 10 mm, which is consistent with the results in the TG 108 report. Some of the PET radionuclides, such as I-124, Zr-89 and Y-86 with many high energy photon emissions require much more lead per HVL than the 5.1 mm of lead for F-18, as the TG 108 report cautions.



Sometimes instruments themselves provide localized shielding. Well counters and dose calibrators are available with shielded chambers. Shielded cabinets are handy for storing sources and phantoms for decay. Both PET/CT and PET/MR scanners provide an appreciable degree of shielding within the shadow of the instrument.

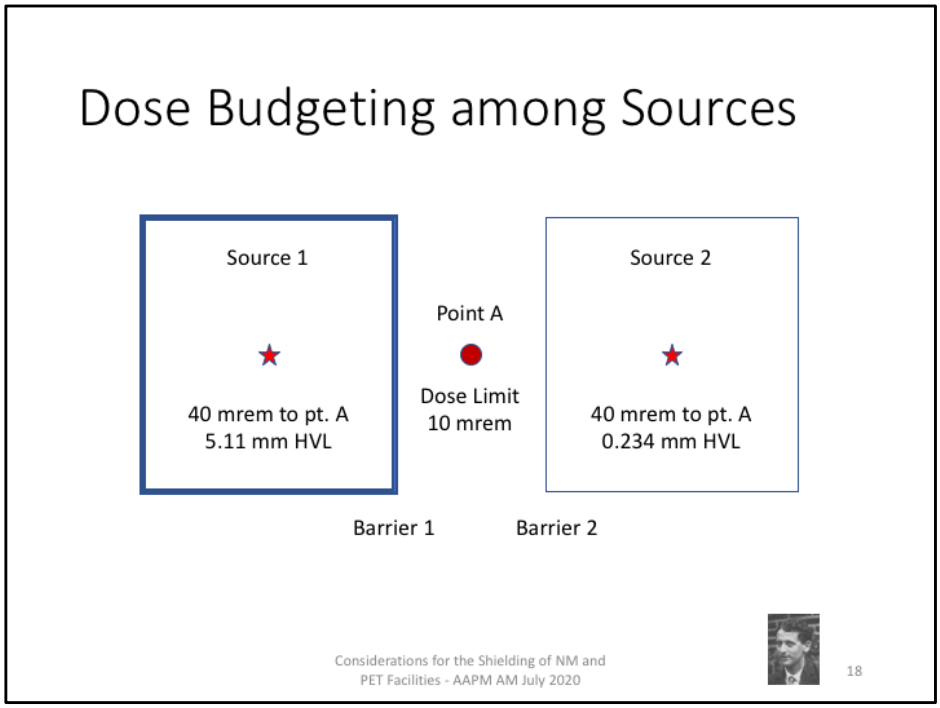


Unity occupancy factors in controlled areas makes sense because the occupants are presumably exposed to radiation somewhere within the controlled area for the entire working day. If fractional occupancy factors are used in different parts of a controlled area, as is deemed to be acceptable in the TG 108 report, then it would be possible for someone who occupies the controlled area continuously to receive a dose that exceeds the design limit. What is more, this does not take into account the possibility that occupationally exposed personnel may be exposed to unshielded patients in the course of their work and thus receive an additional dose that is not factored into the design of the structure shielding if the standard dose limits are used.

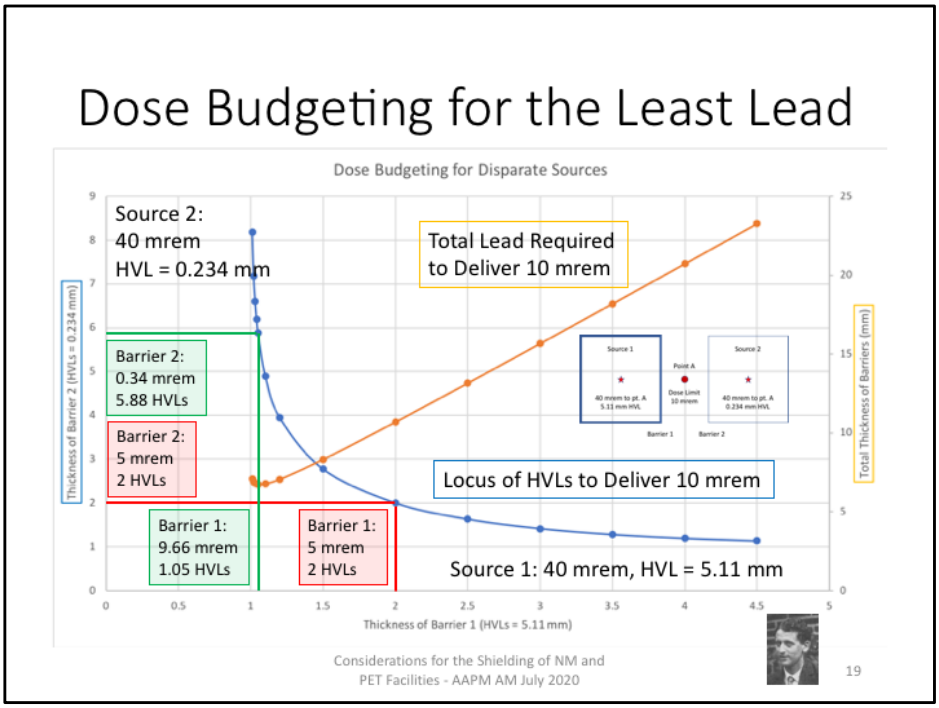
Dose Budgeting among Sources

- In a facility with several different modalities, the dose target should be apportioned among the sources according to the difficulty of shielding them.
- The sources with thinner (i.e., cheaper) half-value layers should be shielded to a lower dose than those with thicker half-value layers.
- The sum of the doses from each modality should not exceed the target dose of the overall shielding.

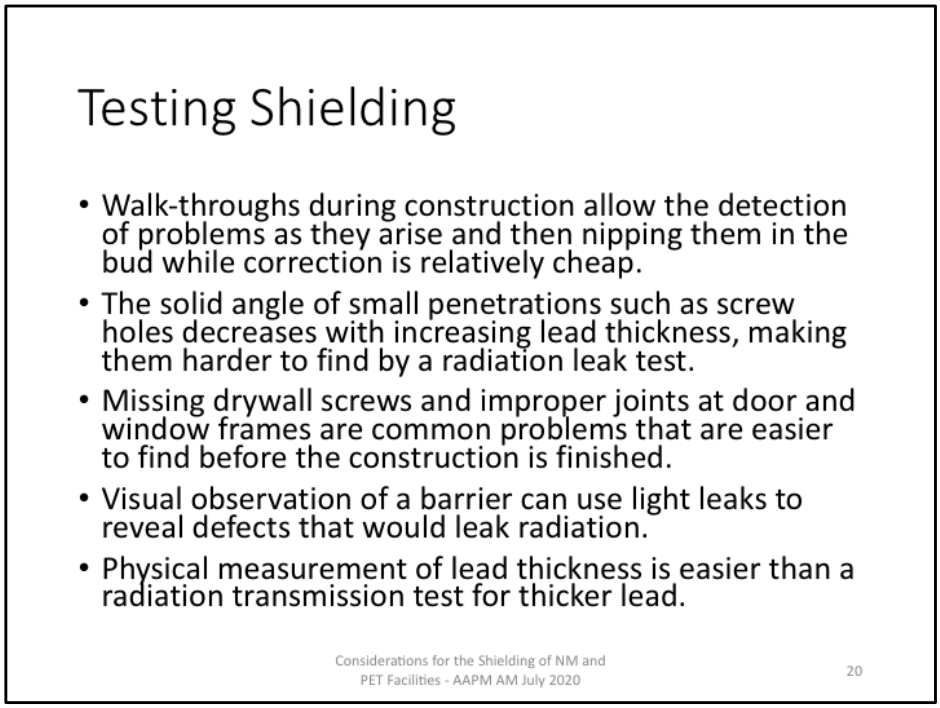
We shield by half-value layers but we pay by the pound, so it makes sense to devote more half-value layers to sources with thin half-value layers and fewer half-value layers to sources with thick half-value layers.



Here's an example of a two sources, each of which would deliver 40 mrem to Point A. We would like to shield Point A to a combined dose of 10 mrem. An HVL of source 1 is 5.11 mm whereas an HVL of source 2 is 0.234 mm. (This sounds a lot like F-18 and Tc-99m, doesn't it?)



The left hand vertical axis is the half-value layers of barrier 2 while the horizontal axis is the half-value layers of barrier 1. The blue line is the locus of HVLs in the two barriers that achieve the 10 mrem design goal The right hand vertical axis is the combined thickness of lead in the two barriers. The orange line is the locus of total lead that is required to achieve the design goal as a function of the number of HVLs in barrier 1. One sees that the minimum total amount of lead is achieved when barrier one is slightly more than one HVL in thickness while barrier 2 is 5.88 HVLs.



Testing thick lead is harder than testing thin lead. We like to participate in the walk-through inspections during construction so that we can comment on construction methods and observe visible defects in shielding as it is being installed and while it is the cheapest to remediate. As the lead gets thicker, holes such as those made by missing screws subtend smaller solid angles and become harder to find in a radiation leak test. Missing screws and poor joints at door and window frames are common problems that we encounter. We can use light leaks through a shielded wall as a readily visualized indicator of possible radiation leaks. Also, it is easier to measure the thickness of lead when a caliper can be used than when a radiation transmission test must be performed.

Summary

- Radionuclides have different emission spectra than radiographic devices.
- Sources are characterized as average activity at particular locations for fractions of the working week.
- Often more than one source irradiates a point that is to be shielded.
- Dose budgeting can be used to optimize the lead that is installed.
- Engagement during construction and visual inspection augments the eventual radiation leak testing of an installation.

References

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These references might be helpful. Note that reference 6 is obsolete because it relies upon old organ weighting factors.