Radiation Shielding for Megavoltage Photon Therapy Machines

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Introduction

The purpose of this refresher course is to review the application of the basic shielding equations for primary, scatter and leakage radiation and discuss general principles of room design and layout. Included in this discussion are the concepts of workload, use and occupancy factors and current regulations on maximum permissible exposure and their effect on design. The special circumstance where an existing facility is upgraded from a low to a high-energy machine where additional shielding space is limited will also be addressed.

In addition to these considerations, particular shielding problems related to high energy machines, such as door shielding for neutrons and capture γ rays at the end of a maze, laminated primary shielding and neutron generation and edge effects for doors that shield for direct secondary radiation from the target will be reviewed. The impact of special procedures such as TBI, SRS and IMRT will also be discussed.

Basic Principles:

The purpose of radiation shielding is to reduce the effective equivalent dose from a linear accelerator to a point outside the room to a sufficiently low level, one that is determined by individual states; this level is generally 0.02 mSv per week for a public or uncontrolled area. Frequently, a higher level is chosen for areas restricted from public access (i.e., “controlled” areas) and occupied only by workers; this limit is 0.1 mSv/wk. The required shielding is calculated based on the weekly workload of the machine, the distance from the target or isocenter to the point being shielded, modified by the fraction of time that the beam is pointed in that direction and the fraction of the working week that the space is occupied.

1. Calculations

Radiation generated by linear accelerators can be divided into primary and secondary components, the latter being divided into scatter and leakage radiation.

a. Primary

Primary radiation is that radiation used to treat the patient. Though the typical treatment field size is generally less than 20 x 20 cm^2, for shielding purposes, the maximum field size of 40 x 40 cm^2 is always assumed (see section on barrier widths). The required barrier transmission factor, B_p, for primary radiation is given by:

$$B_p = \frac{Pd^2}{WUT}$$

where:

P is the weekly design dose limit derived from the annual limit appropriate for the type of space protected by the barrier (Sv/wk).

d is the distance from the target to the point of measurement (m)

W is the workload (Gy/wk)

U is the use factor

T is the occupancy factor

(see section 2 below for definitions of W, U and T).

b. Primary barrier width

The width of the primary barrier is calculated using the maximum diagonal field size at the barrier. This is usually 50 cm and not 40√2 = 56 cm, due to the circular primary collimator. To this projected width is added 30 cm on each side. The distance at which this width is calculated depends upon the way the primary barrier is configured relative to the secondary barrier. Figures 1 and 2 show two alternative layouts for the shielding where concrete only barriers are used. If a uniform thickness laminated barrier with lead or steel is used, the width is calculated at the distal surface of the lead or steel. This is illustrated in Fig. 3.

It should be noted that this 30 cm rule should be used with caution for high-energy beams (≥18 MV), because the scattered radiation at these primary energies can be very energetic and the scatter to incident exposure factor high. The secondary barriers adjacent to the primary barrier must account for 20° scatter radiation, just beyond the primary radiation.

The barrier width should be determined at the inside ceiling height on the outside of the wall that is furthest from the isocenter and maintained constant over the primary barrier region, i.e., both side walls and ceiling. Note that for a wide room with a low ceiling height, the width of the primary beam directly overhead will be considerably narrower than this barrier width. However, this allows for ease of construction since, otherwise, a more complicated form arrangement would be required to provide a tapered primary barrier. Alternatively, part of the ceiling primary barrier can include either lead or steel. These materials come conveniently in either sheets (steel) or bricks (lead), so that the high density shielding can easily be laid over the primary area to include the tapering of the beam across the surface of the ceiling.

There is also a trade-off in terms of the width of the primary barrier and the thickness of the secondary barrier. The thickness of the secondary barrier decreases with distance from the primary beam axis. Therefore, a lower shielding thickness is required, in addition to which, the effect of obliquity (see below) provides an added benefit. Hence, by extending the width of the primary barrier beyond the value recommended above, the adjacent secondary barrier could be made thinner.

Laser lights in the primary beam may require a recess in the concrete if the width of the room is critical for full motion of the linear accelerator couch. This recess thickness is equivalent to about an HVL or so for high energy radiation, so a steel or lead plate with a thickness providing the same attenuation as the removed concrete should be used behind the laser. Since the lasers generally require a mounting plate to allow for lateral adjustments in the position of the laser unit, the two functions can be combined in one plate.

c. Scatter

Scatter radiation is that radiation generated by the patient or by the primary beam (attenuated by the patient) striking a primary barrier. The required barrier transmission factor for scattered radiation, B_s, is given by:

$$B_s = \frac{P}{aWT} d_{sec}^2 d_{sca}^2 \frac{400}{F}$$

where:

a is the scatter fraction for the particular angle and incoming beam energy

d_{sec} is the distance from the scatterer to the point of measurement (m)

d_{sca} is the distance from the target to the scatterer (isocenter distance) (m)

F is the area of the beam in the plane of the scatterer (cm^2)

Scatter fractions are tabulated in NCRP report #151.

d. Leakage

Leakage radiation refers to x-rays generated in the head from interactions of the primary electrons in the target, flattening filter collimator jaws and other surrounding. The required barrier transmission factor for leakage radiation, B_l, is given by:

$$B_l = \frac{1000 * P d_l^2}{WT}$$

where d_l is the distance from the target to the point of measurement. The factor of 1000 stems from the fact that regulations require the leakage radiation at 1 m not exceed 0.1% of the primary beam at isocenter.

These transmission factors are converted to barrier thicknesses using the equation:

$$T = -TVL * \log_{10}(B)$$

where TVL is the appropriate tenth value layer for the radiation under consideration. For primary barriers it is not necessary to include the effects of secondary radiation. However, for secondary radiation, both leakage and scatter should be considered. If the required thicknesses for scatter and leakage radiation, as calculated from the equations above, are within 1 HVL, an additional HVL should be added to the greater thickness. In general however, leakage radiation dominates over scattered radiation, particularly for barriers orthogonal to the plane of gantry rotation. However, for high energy photon beams (≥ 18 MV), the “a” factor for scattering angles less than 30° need special consideration.

e. Obliquity factor

When the angle of the radiation is not orthogonal to the shielding barrier, the required thickness will be less than the calculated thickness by a factor that depends on the angle of incidence. This factor, known as the ‘obliquity’ factor varies as cos (θ), where θ is the angle between the incident ray and the normal to the shielding wall. Thus the effective thickness of a barrier, *t*, is related to the actual thickness, *s*, by the relationship (see Fig. 4)

$$t = s / \cos(\theta)$$

The validity of this relationship is discussed in NCRP report #’s 49 (1976) and 151 (2005) and has been investigated by Biggs (1995) using the Monte Carlo approach. This relationship is certainly valid for all energies and angles of incidence up to 45° for concrete barriers. For higher angles, the two reports should be consulted.

2. *Workload, use and occupancy factors*

a. *Workload*

The workload is the average number of monitor units (MU) of radiation used per week in treating patients over the course of a year. This is equivalent to the number of cGy of x-rays prescribed for treatment at isocenter multiplied by a conversion factor that represents an average monitor unit to dose value to account for different treatment depths, use of wedges, etc. For example, a busy machine that treats 45 patients per day using 3D CRT to a dose of 300 MU/fraction, five days per week would have a workload of 45 x 300 x 5 = 675 Gy/week. However, the planner should determine the value for W from information specific to the logistics at the proposed site. NCRP #151 (2005) provides some guidance and recommendations for typical clinical situations.

In the era of dual energy photon machines, the question arises as to how many MU's to apportion to which energy. Again, it is better to be conservative and assume that all the MU's will be delivered at the higher energy, unless it is clear and can be documented from the patient population precisely what mix of energies will be used. However, when IMRT treatments (usually delivered at 6 MV) are a substantial fraction of the total treatments, a dual workload model should be developed.

(i) Effect of TBI, IMRT, stereotactic radiosurgery and IORT on workload

It has been assumed in the foregoing that the workload for a particular facility is based on a fixed number of patients treated with a daily fractional dose of about 2 Gy. For all these treatments, the ratio of monitor units (MU) delivered by the machine to treatment dose is slightly greater than, but very close to, unity, even for complex plans involving wedges. Thus the workload is essentially equivalent to the total weekly patient treatment dose. However, there are other procedures, such as TBI and IMRT, where this ratio is much greater than unity.

In TBI, for example, the patient is routinely treated at a distance of about 4 m, to achieve the necessary field size to treat the whole patient. Thus the target-to-treatment distance is 5 m and, for a treatment dose of 13.2 Gy over 11 fractions, the number of MUs required to deliver these treatments will be 33,000. Put another way, one TBI treatment per day is equivalent to about 12-13 treatments of standard therapy in terms of the head leakage, but not the primary or scatter radiation.

In IMRT, a significantly higher ratio of MUs per treatment dose arises because, unlike conventional 2D radiation therapy, where the lesion being treated is fully irradiated with each beam, each of the multiplicity of IMRT fields irradiates only a part of the lesion. Hence far more MUs are required to deliver a given fractional IMRT daily dose than for conventional therapy. Since the dose to the target has not increased compared with 3D conformal therapy, only leakage radiation, which depends on exposure time, is increased. For conventional linear accelerators, this increase is on the order of five.

In stereotactic radiosurgery, a dose of 15-20 Gy is normally given to the 80% isodose line, but the treatment session generally lasts about one and a half hours, so the dose rate is about the same as for a busy conventional therapy department.

In IORT, a different situation occurs since large single doses are given to, at most, 10 patients per week. The turn-around time for each surgical case and not the time it takes to set up and irradiate the patient limit this patient load. If the facility is dedicated to IORT, then the workload is based on this figure and, hence, each procedure contributes 10% to the total workload. If the weekly maximum permissible dose limit is set high, the hourly limit could easily be exceeded. For such a facility, therefore, the ‘2 mR in any one hour’ rule should be carefully checked for compliance.

b. Use Factor

The use factor refers to the fraction of time over the course of a year that the primary barrier is pointing at a particular barrier. NCRP #151 (2005) recommends values of 0.213 for walls and 0.263 for the ceiling. In most instances there is no occupied space beneath the room, so the factor for the floor is moot. However, if there were occupied space below the floor, a factor of 0.31 should be assigned. These values assume that treatments are given primarily at cardinal angles. For 45° intervals, NCRP #151 (2005) gives somewhat different values..

In stereotactic radiosurgery, several arcs, commonly five are used to treat a small intra-cranial lesion. This type of treatment does not conform to the use factor specified in NCRP report #49 since, although most gantry angles are used, there is a preponderance of angles around 90° and 270° (IEC system of coordinates) and much less at 0° and 180°. On a polar plot, the distribution of angles would resemble a butterfly.

c. Occupancy Factor

The occupancy factor for a shielding barrier applies to the amount of time the maximally exposed person spends in the area beyond that barrier. NCRP #151 (2005) recommends six specific fractional values for non-controlled areas, depending on the situation. The first, full occupancy, with a value of unity, applies to offices, laboratories, shops, wards, nurses' stations, living quarters, children's play areas and occupied space in nearby buildings. The second, half occupancy, applies to adjacent treatment rooms, patient exam rooms adjacent to shielded vault. The third, one fifth occupancy applies to corridors, staff rest rooms and employee lounges. The fourth, quite a surprise, one eighth occupancy, applies to treatment vault doors. The fifth, one twentieth occupancy applies to unattended waiting rooms, public toilets, storage areas, outdoor areas with seating, janitors' closets, patient holding areas and attics. The sixth and last, one fortieth occupancy applies to outside areas used only for pedestrians or vehicular traffic, unattended parking lots, stairways and unattended elevators. For controlled areas, the occupancy is recommended to be unity. However, since the goal is to shield people and not spaces, documented use of an area or verification using film badges, can justify occupancy factors lower than those recommended, even for controlled areas.

3. Shielding materials

The following materials are used extensively as shielding material for linear accelerator vaults. The list is not complete, but these are the materials that are most commonly used.

a. Concrete

Concrete is an inexpensive shielding material that, once formed, is self-supporting. Its great advantage over other materials is that for high energy machines (>10 MV), if the barrier thickness is adequate to shield against x-rays, it is also adequate for neutrons (but see comment under 'Ducts' below). Thus one only has to worry about doors and large ducts, such as HVAC, for neutron shielding. Note, however, that the neutron shielding effectiveness of concrete does not increase with density since the latter is only changed by adding high Z components that are ineffective against neutrons at these energies. The density of concrete is quite variable, depending on the area of the country, but the standard density is 2.35 g/cm^3 (147 lb/ft^3). If the actual density is less than this, (the density should be verified for the pour at the time of construction) the TVLs should be adjusted accordingly. The shielding designer should confirm with the architects what guaranteed density of concrete the contractor can supply.

By adding aggregate to the mix (e.g., iron barytes), one can achieve densities of 3.85 g/cm^3 (240 lb/ft^3). However, this is less commonly found and hence considerably more expensive than regular density concrete. An alternative high density, low cost shielding material (Barish) has been produced by embedding small pieces of scrap steel or iron in cement. Measured TVLs at 16 MV in these materials were found to be 22 cm and 24 cm respectively, compared with 42 cm for ordinary concrete.

Concrete is also available in the form of interlocking blocks, as in the case of lead (see below) and these come in densities of 240 and 288 lb/cu.ft^3.

b. Lead

Lead has the advantage of high atomic number and density (11.35 g/cm^3) and thus a low TVL. It is therefore a very useful material where space considerations are important. A typical case would be upgrading a room that holds a low energy machine to one for a high energy machine. In this case the lead is generally mounted flush with the walls inside the room. Since lead is not self supporting, it needs to be held in place, usually with 7.5 – 10 cm (3”-4”) steel channel for walls or 20 - 25 cm (8”-10”) I-beams beneath the ceiling. When the lead thickness is equal to or greater than 2.5 cm (1”), lead is conveniently available in interlocking bricks, making construction a straightforward, if arduous, task. However, the fact that lead is relatively transparent to neutrons should not be overlooked.

c. Steel

Steel can also be used in situations where space is important. However, despite its more ‘rigid’ properties, it still needs external support. It is advantageous for laminated shielding for primary barriers compared with lead, since it produces fewer photo-neutrons. The density of steel is 7.8 g/cm^3.

d. Earth

Dry packed earth, which has a density of about 1.5 g/cm^3 (95 lb/ft^3), is a useful, very inexpensive shielding material. This makes it convenient for constructing vaults in an area below ground since the outer concrete walls need only be about 45 cm thick, sufficient to support overhead structures.

e. Polyethylene

Polyethylene is used for shielding against neutrons. It is also available as borated polyethlene, usually in the 5% form, to absorb thermal neutrons. The density of polyethylene is 0.95 g/cm^3.

4. Tenth value layers (TVL)

The table below shows TVLs for primary x-rays in concrete, lead and steel for some typical accelerator energies; these values have been taken from NCRP report #151 (2005).

TVL (cm)

Energy (MV)	6	10	15	18
Concrete	37 (33)	41 (37)	44 (41)	45 (43)
Lead	5.7	5.7	5.7	5.7
Steel	10	11	11	11

The first numbers indicates the first TVL and the number in parenthesis indicates subsequent TVLs.

For neutron shielding, the TVL in polyethylene for fast neutrons is 10.2 cm compared with 20.3 cm for concrete. For neutrons striking the door at the end of the maze, typically 100 keV, the TVL is 4.5 cm. Likewise, the TVL for capture γ rays at the end of a maze is 6.1 cm.

The TVLs for leakage radiation depend strongly on the angle of the radiation relative to the central axis of the primary beam. The TVL decreases as this angle increases from the forward to the backward direction. TVLs are provided for leakage radiation at 90° in concrete for a number of primary beam energies; this TVL is appropriate for calculating the shielding for barriers in the planes orthogonal to the primary beam axis. These values are given in the table below.

	TVL (cm)					
Energy (MV)	6	10	15	18	20	25
Concrete	34 (29)	35 (31)	36 (33)	36 (34)	36 (34)	37 (35)

5. Room Layout and features

a. Overall size

One can estimate the minimum total square footage required for an accelerator vault from the area required for the machine and couch together with the space required for cabinets, shielding, maze etc. Typically, as shown in Fig. 5, the couch has a swing radius of about 2.75 m (9’) in the fully extended position, although Elekta machines have a couch extension of about 1.8 m (6’). Along the gantry direction a distance of about 5.6 - 6.4 m (18.5’ - 21’) is required between the back wall and the end of the couch when fully extended. Thus, allowing for clearance one needs a clear area of up to 6.1 x 6.7 m^2 (20’ x 22’) inside the room. Storage cabinets along any of the walls would require an additional 60 cm (2’).

A minimum height of 3 m (10’) is required for the ceiling to accommodate the machine and the entire duct work and conduits necessary for the room as well as the overhead laser. A false ceiling can be made at a height of 2.75 m (9’) to accommodate the height of the machine with adequate clearance. In theory, a room height of 2.75 m could be used, but this could cause many architectural problems. The height of the ceiling should not greatly exceed 3m since this only increases unnecessary construction costs.

b. Machine orientation

There are three possible general orientations of the machine inside the room where a maze is included in the design: (i) the plane of gantry rotation is parallel to the maze; (ii) the plane of gantry rotation is orthogonal to the maze; (iii) the plane of gantry rotation is at some angle with respect to the walls, other than 0° or 90° and usually 45°. The first two orientations are shown in Fig 6 and the third in Fig. 7. It is worthwhile briefly discussing each option. In the first case, the maze is not the primary barrier so that one need only be concerned with secondary radiation for the maze and door, thus simplifying the calculation. Also, from the therapist’s standpoint, this has the advantage that, when stretchers are wheeled into the room, only one 90° turn has to be negotiated. In the second case, where the primary beam strikes the maze wall, a full 180° turn has to be negotiated for the stretcher. The shielding calculations can also be more complicated and may require a thicker door at the end of the maze.

There are occasions, however, when, for reasons of space, esthetics or patient set-up convenience, it is desired to place the linear accelerator in the room with its axis of gantry rotation at, for example, 45° with respect to the walls of the room. Great care has to be exercised in the design of the primary barrier for this situation, since photons travelling along the two opposite diagonal edges of the beam traverse the shielding at different angles. Thus, the position along the outside of the shielded wall at which the two edges of the primary beam strike the barrier can be quite asymmetric with respect to the central axis of the beam. These two positions are denoted by A and B in the Fig. 7. Note, however, that advantage can be taken of the obliquity factor in calculating the shielding thicknesses, although great care must be exercised.

Another beam orientation sometimes used that requires special consideration is when the primary beam hits the outer maze wall (Fig. 8), the inner maze wall only being long enough to prevent leakage from the head and scatter from the patient reaching the door (Biggs 1991). The problem is that the NCRP report #151 (2005) does not provide scatter coefficients for this situation. If one looks at the source of this data (Chiltern et. al. 1984), one finds that the scattering coefficients go to zero as the scattering angle reaches 90°. Clearly, not all photons are scattered at 90° and, moreover, the scattering process is not a simple single scatter situation (Lo 1992). The solution to the problem can be solved using either a Monte Carlo approach or a more detailed calculation using the NCRP methodology (Biggs 1991).

c. Maze vs. direct door

One of the choices to be made in designing a room is whether to use a maze or a direct shielded door. In many cases, where the available space is minimal, there may be no choice but a direct shielded door. However, where there is a choice, one should be aware of the advantages and disadvantages of the two systems. A direct shielded door has the advantage that the amount of room space will be greater than for a room with a maze for the same overall area. It is also chosen over a maze by many institutions because it provides easier access to the room for the therapists (80 patients per day at 4 fields per patient is a large number of trips, although this will be less with conformal therapy and IMRT). However, a direct shielded door is very heavy and expensive, particularly for machines with energies ≥ 15 MV where the neutron shielding becomes significant. Use of a maze has the advantage that the door will be significantly lighter, though for high energy, neutron-producing machines, a non-trivial thickness, and therefore weight, of lead and polyethylene is still required.

d. Physics' conduit

For new rooms, a 10 cm inner diameter aluminum or PVC pipe, rising from just above floor level inside the room (about 7 - 10 cm) to just above counter-top height at the console, should be included in the concrete form-work (see Fig. 9). For remodeled rooms, this requires coring a hole not less than 10 cm in diameter through the concrete wall also between a point just above the floor inside the room and a point just above the counter top outside the room. However, because of existing millwork or plumbing constraints inside the room, it may also be necessary to angle the hole in the horizontal direction. Fitting a metal or PVC sleeve in the cored hole is desirable because of the problem of residual concrete dust affecting the chamber or cable connectors. Using such an arrangement, it is generally unnecessary to include additional shielding material either to account for the void in the wall or for scattering along the pipe.

e. Safety features

In addition to the design features listed above, a number of safety features need to be included in the design of the room, some mandated by State and Federal regulations. The first is the requirement of door interlocks such that if the door is opened while the beam is on, the machine is shut off. An elaboration of this feature is the ‘search button’ that requires the room to be searched and, after closing the door, the beam must be turned on within a predetermined period. The purpose of this feature is to ensure that the door cannot be closed and the beam turned on unless the room has been checked to ensure no personnel are present. TV cameras and intercom systems to observe and communicate with the patient are also necessary. Warning lights outside the room are important to inform personnel about the status of the room, whether it is accessible, closed or the beam is on. Warning lights inside the room are useful but not necessary. A number of emergency-off buttons are provided with the machine and located on the couch, the gantry stand, modulator (if there is a separate unit) and control console. It is a good idea to have additional emergency-off buttons, located in a clear and accessible position on each wall, but protected from accidental activation.

f. Upgrading rooms to high energy

There is a frequent need to re-shield a room that holds a low energy machine, such as a 4 or 6 MV, for a dual energy machine with a maximum photon energy of 15 or 18 MV. The re-shielding is required because of the difference in TVL in concrete between the low and high energies. The difficulties encountered in making this change depend heavily upon the space within the room and also the surrounding areas. If sufficient space exists, then either poured concrete or concrete blocks can be used for the additional shielding. If, as occurs in most cases, there is little extra space inside the room (and usually none outside) for added shielding without compromising the operation of the linear accelerator, such as the couch rotation for example, then either lead or steel will have to be used. Lead is perhaps preferred since although it requires structural support, steel is also not easily added in large sizes without structural support and lead has the advantage that its TVL is half that of steel. However, it should be noted that steel has the advantage of lower photoneutron production.

The first step is to calculate how much additional lead is required to meet the regulatory requirements outside the room. This will certainly be greater than 2.5 cm (1”), so interlocking bricks can be used. Note that if a room previously housed a machine with a beam stopper, 3 TVLs of shielding are required on top of any TVL differences in concrete between low and high-energy machines. Based on the discussions of photoneutron production in section 7 below, it is always desirable to place the high Z material on the inside of the room.

For walls, the lead can be easily stacked and held in place using 7.5 or 10 cm (3”-4”) steel channel, as shown in Fig. 10. For ceilings, the issue of weight is a serious problem and steel I-beams must be used to support the weight. Depending on the weight supported, either a single array of 20-25 cm (8”-10”) I-beams or a double array (Fig. 11), by adding an orthogonal array of 40-45 (18”-20”) cm I-beams, could be used. Depending on the space available, the additional shielding can be placed above the I-beams or between the I-beams, supported by steel plates (Fig. 11).

6 *Neutrons*

Since the threshold for photoneutron production on lead is about 8 MeV, contamination due to neutrons is not a problem for therapy beams below 10 MV. At this energy, the production of neutrons is still quite low, but should be taken into account. By 15 MV, neutron production increases by a factor of ten and by 18 MV a further factor of two (Elsalim 1994).

The neutron fluence can be calculated for a room of a given size through a method given by McCall et. al. outlined in NCRP report #79. Based on an analysis of Monte Carlo results for rooms of varying sizes and dimensions, McCall developed a simple formula that related the neutron fluence, Φ, to the inside surface area of the room, S, the distance between the source and the detector, d, and the number of fast neutrons, Q.

$$\Phi = \frac{Q}{2\pi}\left(\frac{c}{2d^2} + \frac{5.4c}{S} + \frac{1.26}{S}\right)$$

where c is a constant for a given accelerator and equal to 0.85 for an all tungsten shielded machine and 1.0 for an all lead shielded machine. This equation differs from that given in NCRP report #79 by a '2π' factor for the scattered and thermal neutrons. The average energy can be derived from this fluence and, in turn, the neutron dose can be calculated from the fluence to dose conversion factors given graphically in NCRP report #79. This 'cookbook' method is said to agree with Monte Carlo results to within 10%. McGinley (1998) has provided Q values for a number of current linear accelerators.

7. Laminated shielding

When space does not permit the full thickness of the primary barrier to be made of concrete, so-called 'laminated shielding' can be used. This consists of a thickness of concrete, often equal to the thickness of the adjacent secondary barrier with the remainder of lead or steel added to the upstream end. This would be added after the concrete barrier has been constructed. Alternatively, the steel or lead can be added as part of the concrete structure to maintain a constant wall thickness.

To calculate the thickness of steel or lead required in the first case where they are added to the concrete barrier, one simply needs to know how many additional TVLs of shielding are required. In the second case, one is constrained by the overall thickness of the barrier and one has to solve an equation for the thickness of the lead or concrete.

The disadvantage of using lead or steel as part of the primary barrier is that photo-neutrons can be produced in these materials. It is therefore important that these materials are closest to the target in the shielding barrier so that the concrete can effectively absorb the neutrons. For walls, this is no problem since they can easily be mounted on the inside; for the ceiling this is more complicated since sufficient concrete has to be laid first to support the lead or steel. This thickness would be about 46 cm (18"). McGinley (1992) has derived a formula to determine the dose equivalent rate from neutrons, *H*, when a primary beam strikes a laminated barrier (Fig. 13)

$$H = \frac{D_x R_n B}{T/2 + X_2 + 0.305} * 10^{-X_1/TVLX} * 10^{-X_2/TVLN}$$

where H is the neutron dose equivalent rate (μSv s^{-1})

D_x is the x-ray dose at the isocenter (cGy s^{-1})

R_n is neutron production rate (μSv neutron cGy^{-1} x-ray m^{-2} beam area)

B is the maximum beam area at isocenter (m2)

T is the thickness of the metal slab (m)

X_1 is the thickness of the first concrete slab (m)

X_2 is the thickness of the final layer of concrete (m)

TVLX is the tenth value layer in concrete for primary x-rays (m)

TVLN is the tenth value layer in concrete for photo-neutrons (m)

and *0.305* corresponds to 1', the distance beyond the barrier at which measurements are made.

Values for Q given by McGinley, based on measurements on 18 MV x-ray beams are 19 and 1.7 μSv per cGy x-ray m^2 beam area for lead and steel respectively. For 15 MV x-rays, the value decreases by a factor of 5.4 for lead. Thus it is advantageous to use steel instead of lead, if the extra thickness is permitted, and to reduce the energy to 15 MV.

On a practical note, if the primary barrier is a wall, then the interlocking lead bricks can be stacked vertically and held in place with 7.5-10 cm (3"-4") steel channel, spaced about 45 cm (1½') apart. If the primary barrier is the ceiling, a minimum underlying thickness of concrete of 30-45 cm (1'-1½ ') is required to support the weight of the lead which reduces the effective thickness of concrete for stopping neutrons. Also, on a minor note, if lead is buried in the concrete, it must be covered with tar paper or painted with tar to prevent oxidation from moisture in the concrete.

8. Doors and mazes

a. Maze doors

b. Low energy

The formalism for calculating the dose at the door due to scatter of secondary radiation is described in NCRP report #151 (2005).

When calculating the radiation incident on the door at the end of the maze, one has to take into account several sources of secondary radiation. These include leakage from the head, L_I, scatter radiation from the patient, S_p, and scatter radiation from the primary beam hitting the primary barrier, S_s, all down the maze, and leakage from the head penetrating the inner maze wall, L_d.

L_I Leakage from the head that is scattered down the maze is illustrated in Fig. 14. As in the case of patient scatter, radiation, from the target in this case is scattered by the wall maze towards the maze door. The formula from this process is given by

$$L = \frac{L_0 D_0 \alpha_1 A_1}{(d_s d_1)^2}$$

where L_0 is the leakage factor, taken at 1m from the target

D_0 is the dose at isocenter

α_1 is the refection coefficient for the leakage radiation from the back wall in the direction of the maze

and A_1 is the area of the back wall seen by the maze in m^2.

S_s The dose from primary radiation scattered from the primary barrier towards the maze and in turn down the maze, may seem, at first sight, to be small due to the double scattering of the beam and the angles of the scattered radiation (see Fig. 15). However, due in part to the size of the primary beam at the primary barrier, it has been shown that this contribution is not negligible. The formula for this contribution is given by

$$S_s = \frac{D_0 \alpha_1 A_1 \alpha_2 A_2}{(d_i d_{r1} d_{r2})^2}$$

where α_1 is the reflection coefficient for primary radiation scattered from the primary barrier

α_2 is then reflection coefficient for secondary radiation scattered at the maze wall

A_1 is the area of the primary barrier struck by the primary beam

A_2 is the area of the back wall seen by the maze

d_I is the distance from the target to the primary barrier

d_2 is the distance between the center of the primary barrier and the maze wall

and d_s is the distance along the maze

S_p The contribution from the patient scatter can be understood with reference to Fig. 16. The primary radiation is scattered by the patient in the direction of the maze, at a distance d_{sca}, where it is scattered by the back wall down the maze of length d_s. The formula for this component is given by

$$S_p = \frac{aD_0(F/400)\alpha_1 A_1}{(d_{sca} d_{sec} d_s)^2}$$

where α_1 is the reflection coefficient for scattered x-rays from the back wall to be found in NCRP report #51

A_1 is the area of the back wall seen by maze door

and d_s is the length along the maze

a, F, d_{sca} and d_{sec} are defined in section 1b.

McGinley and James (1997) showed that, whereas for patient scatter and room scatter, secondary radiation at the maze door was found to be greater when the beam was pointing towards wall B (see Figs. 14-16), leakage radiation showed no such preference.

L_d This contribution is made up of the leakage from the head of the machine reduced by inverse square to the maze door, attenuated by the thickness of the maze wall (see Fig. 17). Thus the formula becomes

$$L = \frac{L_0 D_0 10^{-(t/TVL)}}{\left(d_{l\text{-}d}\right)^2}$$

where L_0 is the conventional leakage, defined at 1 m from the target

t is the thickness of the maze wall

TVL is the tenth value layer of the maze wall, usually concrete

and $d_{l\text{-}d}$ is the distance from the target to the maze door

The total dose at the door is given by the sum of the four contributions

$$S_t = S_s + L_I + L_d + S_p$$

c. *High energy*

d. *Neutrons*

Kersey has provided a simple method for determining the neutron fluence at the end of a maze. This formalism is based on a two step process which consists of determining (a) the fluence at the entrance to the maze and (b) the attenuation of the neutrons down the maze. In the first step the inverse square is used to calculate the fluence from the effective dose at 1 m from the target and in the second step, the attenuation is calculated assuming a tenth value attenuation factor of 5 m. Thus, the formula is expressed as

$$H = \frac{H_0}{d_1^2 10^{-d_2/5}}$$

where H is the neutron dose equivalent at the maze door

H_0 is the neutron dose equivalent at 1 m from the target

d_1 is the distance between the target and the entrance to the maze

and d_2 is the length of the maze

Since the kersey formula is not in complete agreement with experimental findings, Wu and McGinley (2003) have studied a number of linear accelerator mazes with high energy accelerators and derived the following equation to fit the data.

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

where $H_{n,D}$ is the neutron absorbed dose equivalent at the maze entrance in Sv/Gy at the isocenter. Units are Sv n-1 m2.

ϕ_A is the neutron fluence per unit of absorbed dose of photons at the isocenter (m^{-2} Gy^{-1}).

S_0/S_1 is the ratio of the inner maze entrance cross-sectional area to the cross-sectional area along the maze

and TVD is the tenth value distance (m) that varies as the square root of S_1 ($TVD = 2.06\sqrt{S_1}$)

(2) Capture γ rays at the end of a maze

McGinley, Miner and Mitchum have provided a formalism for determining the production of capture gamma rays in a maze. The starting point is the neutron fluence at the entrance to the maze which can be calculated from the formalism given in section 6 above. With this value for the neutron fluence, the production of capture gamma rays is determined using the following equation

$$D = K\Phi_{total}10^{-d_2/TVD2}$$

where d_2 is the length of the maze and TVD2 is the tenth value distance for γ rays along the maze and equal to 5.4 m. Note that this formalism is only valid for long mazes (>3m). The value of the constant, K, is quoted as 6.9 x 10^{-12} cm^2 Gy. NCRP report #79 suggests that the overall door weight can be reduced by adding an inner door to the maze to reduce the thermal neutron fluence and hence the capture gamma rate. McGinley and Miner and, independently, Ipe et. al. have experimentally verified this theory.

e. Direct shielded doors

(i) Low energy

Calculation of the required shielding thickness of direct shielded doors for low energy machines (below the neutron threshold at 10 MV) only requires consideration of the leakage component from the machine. This is therefore a straightforward application of the calculation shown in section 1 above. Lead is the shielding material of choice for this situation and this is contained in a steel frame whose thickness should be included in the calculation (note that at megavoltage energies, the TVL, in cm, for lead is approximately half that for steel). For a workload of 1000 Gy/week, a distance of 4 m and a maximum permissible dose of 0.02 mSv/wk, a lead thickness of about 16 cm (6.5”) is required, assuming the leakage TVL value shown in the lower table in section 4. A door to support this lead would require 0.625 cm thick steel side plates. The thickness of the concrete surrounding the door should be equivalent to the lead thickness.

There should be adequate overlap of the door with the jamb – NCRP #49 uses a 10:1 rule of thumb for the ratio of the overlap width to the gap between the door and the frame. The gap between the door and floor should be as low as possible, consistent with adequate opening of the door. A gap of 6.25 mm should be readily obtainable, so an overlap of about 5 cm is adequate.

(ii) High energy

Direct shielded doors for high-energy machines (≥ 10 MV) require neutron shielding in addition to x-ray shielding. Using the same figures as in the above example (workload of 100,000 cGy/wk; distance of 4 m; maximum permissible dose of 0.02 mSv/wk) and assuming a photon beam energy of 15 MV, one finds that a lead thickness of 16.5 cm and polyethylene thickness of 36 cm is required. Note that in these calculations, the assumption has been made that the photon and neutron each contribute half to the total dose of 0.02 mSv/wk. With these thicknesses and consequent weight of this shielding, only sliding doors are feasible. A layout for such a door is shown in Fig. 18. Note that the lead has been divided into two sections, one 5 cm thick on the inner room side and the remainder, 10 cm thick, on the outer side. Also, the end sections of the doors are filled either with lead or steel to protect against photons that scatter sideways in the polyethylene.

f. Edge problem for high-energy direct-shielded doors

The problem with direct shielded sliding doors is that of adequate shielding in the overlap region distal to the source. It can be seen from Fig. 19 that rays passing through the edge of the concrete shielding that forms the doorway do not pass through sufficient concrete. A retaining wall of concrete or lead can be built at the end of the door to account for this ‘missing’ shielding.

It is therefore important point to note that when designing sliding doors of this type, the door should slide open in the direction of the isocenter. Failing this, to resolve this problem, one can extend the width of the door, a quite costly solution, or one can add a strip of lead in front of the concrete, either on the doorway wall or the outside wall.

d. Other considerations

A lintel should be built over the entrance between the end of the maze and the room from the maze wall to the outer wall (see Fig. 20). This height of this lintel should be set as low as possible, consistent with rigging the machine into the room and general use of the facility. This could be 213 cm (7’), but generally 244 cm (8’) is used. The purpose of this lintel is to reduce the aperture for scattered radiation, particularly neutrons, to enter the maze (see section 8 above).

9. Ducts

Ducts can be divided into several types according to function and hence, size. The largest ducts are usually for HVAC and two ducts, entry and return, are required for the treatment room. The cross-sectional area of these ducts can be as large as 60 x 30 cm^2. The next largest ducts are usually for machine cables and these typically measure 30 x 10 cm^2 in cross-sectional area. A circular duct, not less than 10 cm in diameter is required for physics purposes. Electrical and water ducts are circular in cross-section and are typically less than 10 cm in diameter.

The purpose of correctly orienting the duct is to ensure that (i) the least amount of concrete is displaced by the duct in the direction of the beam and (ii) the direct radiation through the aperture is minimized. Figure 21 illustrates the principle embodied in (i). The ducts may exit the room at an angle to the wall to maintain this short path or they may be staggered through the wall. Ducts should never be placed in the primary barriers, no matter how small.

Specific requirements for different types of ducts are listed below in order of decreasing size of the duct.

a. *HVAC ducts*

(i) General

Because of their large cross-sectional area, it is important that these ducts are placed in such a way that radiation passing through them will require the least amount of remedial shielding. This will depend on the highest energy available from the linear accelerator as well as the layout geometry. For the case where the ducts pass through the walls, it is important that the ducts should be placed as high as possible to reduce the amount of downward scattered radiation and, hence, to minimize the exposure to personnel outside the room.

Three options are discussed below for (1) rooms with mazes, (2) rooms without mazes and (3) ducts that pass through the ceiling.

(ii) Rooms with mazes

For rooms that incorporate a maze, the logical place for the duct penetrations is directly through the shielding above the door since the photon and neutron fluences are lowest here. To assess the need for additional shielding around the ducts, one first assumes that the photon and neutron dose equivalent rates at the entrance to the ducts are the same as those at the door. One then has to calculate the effect of this radiation scattered to a person directly outside the door. For low energy machines, <10 MV, no additional shielding around the duct is generally required. For high energy machines, McGinley (1998) has shown that, for a primary photon energy of 18 MV, the need for additional shielding depends strongly on the length of the maze. For a maze 5 m in length, the total dose equivalent at the duct amounts to 0.07 mSv/wk, so no additional shielding is required. However, for a 2 m maze, the total dose equivalent is about 0.5 mSv/wk, with equal contributions from photons and neutrons. The preferred arrangement is to bend the ducts immediately after they have exited the maze (see Fig. 22), but if that is not possible, they must be wrapped with lead and borated polyethylene along the duct, as shown in Fig. 23. McGinley (1998) reports that for an 18 MV primary beam, a dose equivalent reduction of four for neutrons and two for photons will be produced by a 1.2 m long duct wrap composed of 2.5 cm polyethylene and 1 cm lead in a 3.6 m maze. For thermal neutrons, the rule of thumb is that a factor of ten can be gained by using a duct length of 2-3 times the square root of the duct cross-section. A third alternative, albeit a more expensive option, is to use the concrete shielding as a baffle, as shown in Fig. 24. Here two parallel, overlapping sections of concrete provide a vertical 'mini-maze.' For this arrangement to be successful, the degree of overlap should be as large as possible.

For rooms that include more than one bend in the maze, duct shielding is unnecessary.

(iii) Rooms without mazes

For rooms that do not have a maze, the walls parallel to the gantry rotation plane are the best for duct placement, because the radiation shielding requirements are lower for these walls than for those in the gantry rotation plane. Since the whole length of the wall can be used for duct placement, the ducts can be angled in the horizontal plane as shown in Fig. 21. This will minimize x-ray scattering through the duct so that only the effect of missing shielding material need be taken into account. This missing thickness amounts to about one TVL or so. Since the duct penetration is high up on the wall, about 10’ above floor level, a simple calculation for 90° scatter shows that the exposure to a person outside the wall should not exceed the maximum permissible dose, if the direct shielding is adequate. The neutron situation is another story and the dose equivalent outside a room from neutrons scattering through a duct is very difficult to calculate. As a practical measure, one should ensure the tightest possible bend in the duct, preferably outside the room, and wrap the duct tightly with up to 10 cm borated polyethylene.

An example based on an actual experience is worth mentioning here. A room without a maze was designed for a 15 MV linear accelerator using high-density concrete blocks as the main shielding material. The HVAC ducts exited the room in a ‘Z’ fashion directly above the console area. Since the wall thickness was thinner than usual by virtue of the block density, it turned out that there was insufficient neutron shielding in the duct area, resulting in an unexpectedly high neutron dose at the console area. Borated polyethylene was placed around the exiting ducts and along the wall to solve this problem.

(iv) Ducts passing through the ceiling

It is important to design a cross-section for the duct that is as rectangular as possible, that is, the duct has a high aspect ratio. The secondary radiation from the target in the direction of the duct should then be as orthogonal as possible to the axis of the duct and also to the longest side of the duct, as shown in Fig. 25. If the duct is angled 90° directly above the ceiling, appropriate shielding can be readily applied, if necessary. However, if one takes into account the extra distance to the floor above and the thickness of the floor above the ceiling (typically, 10-15 cm of concrete), most likely no extra shielding will be required.

b. Machine cables

These are usually placed at ground level inside the room, often below ground, and either angle up to the control area outside or pass directly outside, if below ground level. They generally do not require additional shielding, unless for some reason, the console area is behind a primary barrier.

c. Water and narrow electrical conduits

These conduits are usually less than 2.5 cm in diameter and no special precautions are needed, provided the placement guidelines noted above are adhered to. It is unwise to build these pipes directly into the concrete form work because of possible failure and difficulty of replacement. Rather, a hole of lightly larger diameter than the required conduit is placed in the concrete form work so that the conduit can be readily passed through it on installation.

10. Skyshine

Skyshine refers to radiation scattered by the air above a facility that either has little or no roof shielding, i.e., insufficient to attenuate significantly the primary beam when it is pointing directly upwards. This situation is illustrated in Fig. 26 for photon skyshine. The methodology for calculating photon skyshine is given in NCRP report #151 (2005). Using the terms shown in the figure, the dose equivalent rate, D (nSv s^{-1}), at a distance, d_s, from the isocenter is given by

$$D = 0.249 * 10^6 \frac{B_{xs} D_{io} \Omega^{1.3}}{(d_i d_s)^2}$$

where B_{xs} is the roof shielding transmission ratio

Ω is the solid angle of the beam (steradians)

d_1 is the distance between the target and a point 2 m above the roof (m)

and D_{io} is the x-ray dose at 1m from the target (cGy s^{-1})

Similar arguments can be made for neutron skyshine. The geometry for this component is shown in Fig. 27. Note that in the neutron case, the beam is pointing downward so the target is at its highest point. The equivalent equation is given by

$$H = 0.84 * 10^5 \frac{B_{ns} \Phi_o \Omega}{d_i^2}$$

where H is the neutron dose equivalent rate at ground level (nSv s^{-1})

B_{ns} is the roof shielding transmission ratio for neutrons

D_1 is the distance from the target to the ceiling plus 2 m (m)

Φ_0 is the neutron fluence rate at 1 m from the target (cm^{-2} s^{-1})

and Ω is the solid angle of the shield walls subtended by the target

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Figure Captions

1. Primary barrier width with shielding protruding into the room.
2. Primary barrier width with shielding protruding outside the room.
3. Primary barrier where lead or steel is added to the concrete to ensure a wall of uniform thickness.
4. Sketch illustrating parameters used in obliquity equation.
5. Sketch showing minimum dimensions of interior of a therapy room.
6. Illustration of two possible primary beam orientations with respect to the maze.
7. Case where primary beam is angled at 45° with respect to the wall. Note the difference in path lengths for the limiting rays of the primary beam.
8. Case where primary beam strikes the outer wall of the maze and once-scattered radiation is incident upon the door.
9. Physics conduit.
10. Arrangement for adding lead to the inner wall of an existing therapy room.
11. Arrangement for supporting lead beneath an existing concrete shielding. The lower, orthogonal set of I-beams may not be necessary, depending on the weight of the lead.
12. Arrangement for supporting additional lead when space below the ceiling is limited.
13. Sketch illustrating the parameters used in the equation to determine the production of photoneutrons outside a laminated barrier.
14. Leakage radiation scattered towards the maze door.
15. Primary radiation scattered towards the maze door.

16. Patient scatter scattered towards the maze door.

17. Leakage radiation penetrating the inner maze wall.

18. Door shielding layout for high energy linac for room with no maze.

19. Edge effect for direct shielded doors.

20. Location of lintel at end of inner maze wall.

21. Principle of optimizing duct orientation in shielding barrier.

22. Duct shielding beyond maze door.

23. Alternate arrangement for duct shielding.

24. Alternate arrangement for duct shielding

25. Shielding for duct that penetrates the roof.

26. Diagram showing parameters used in calculating x-ray skyshine.

27. Diagram showing parameters used in calculating x-ray skyshine.

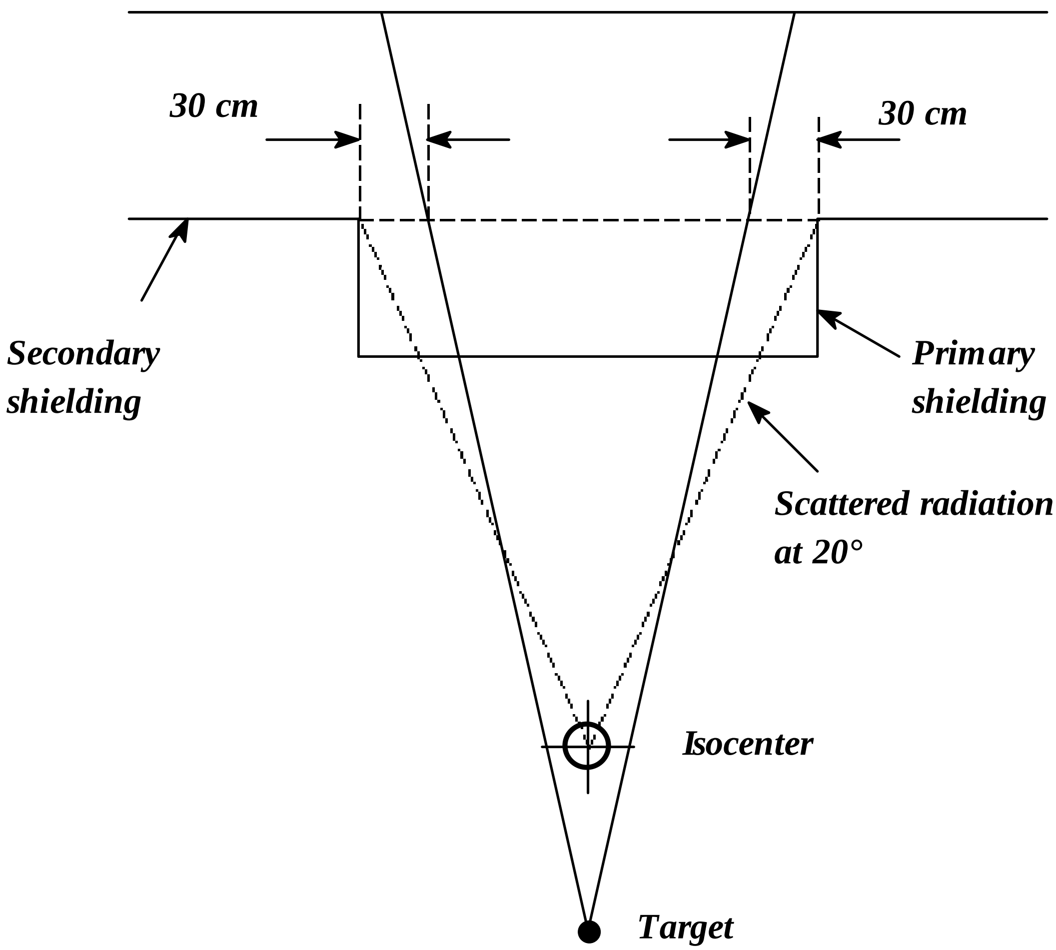

30 cm
30 cm
Secondary shielding
Primary shielding
Scattered radiation at 20°
Isocenter
Target

Figure 1

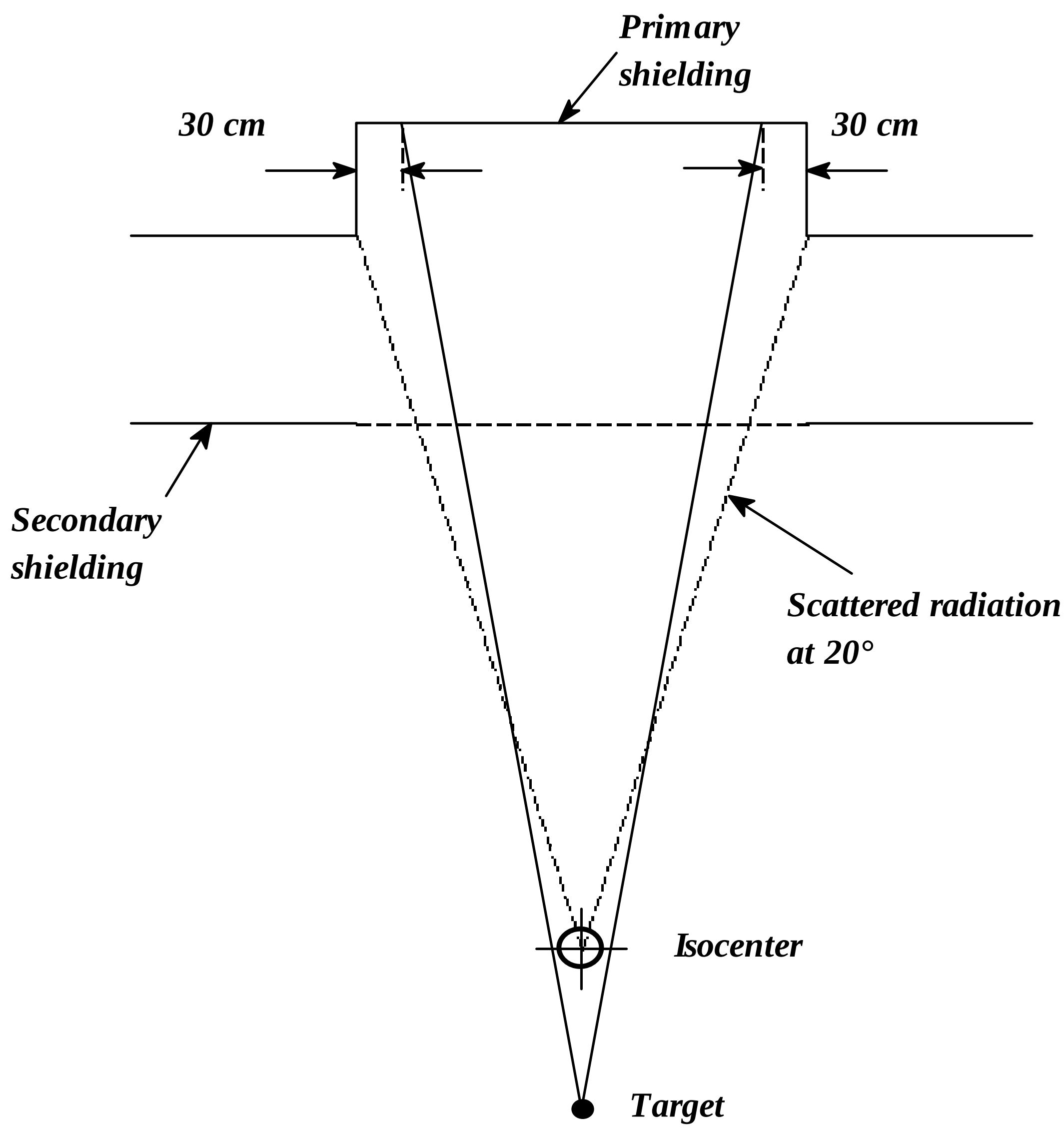

Primary
shielding
30 cm
30 cm
Secondary
shielding
Scattered radiation
at 20°
Isocenter
Target

Figure 2

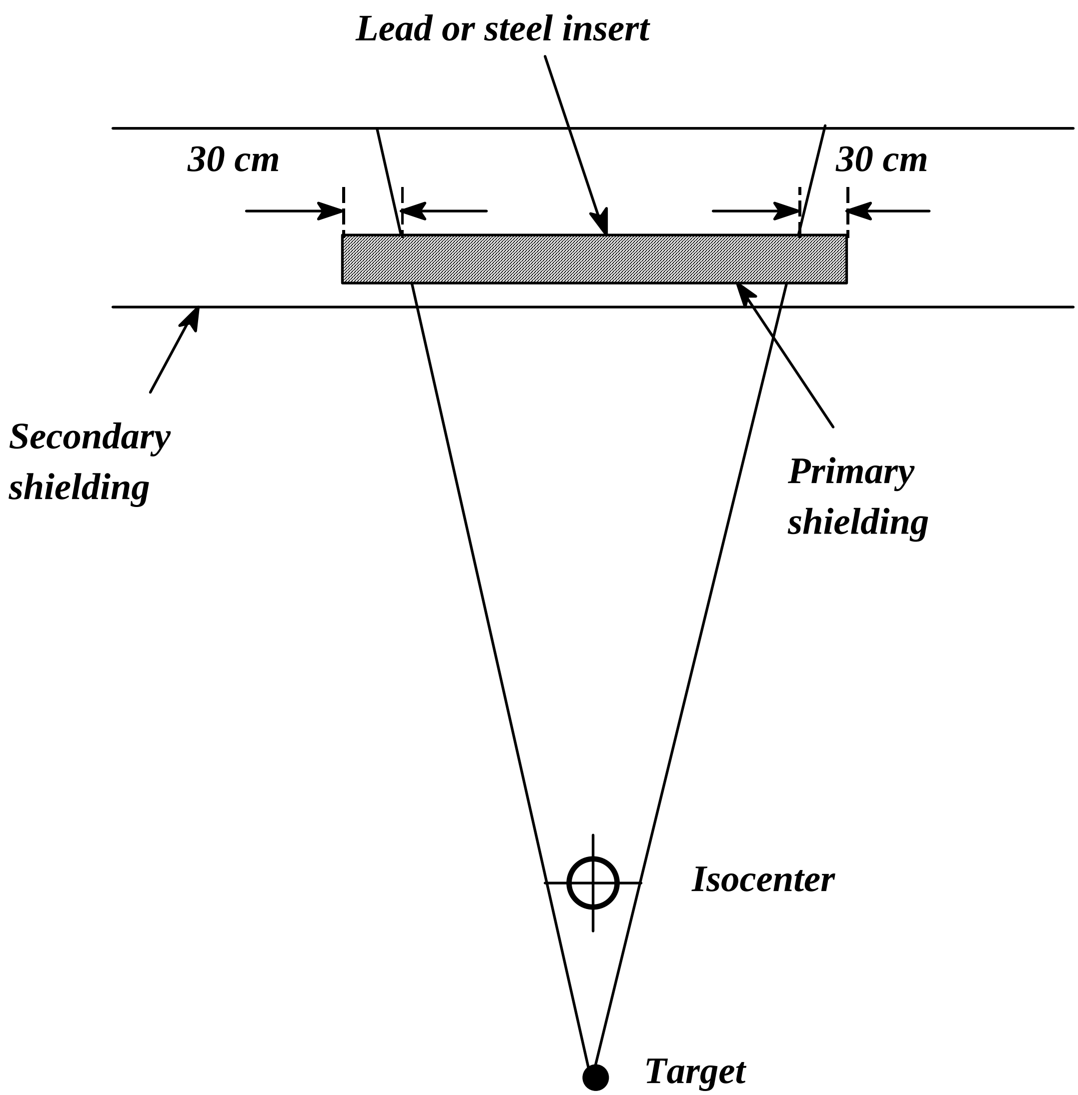
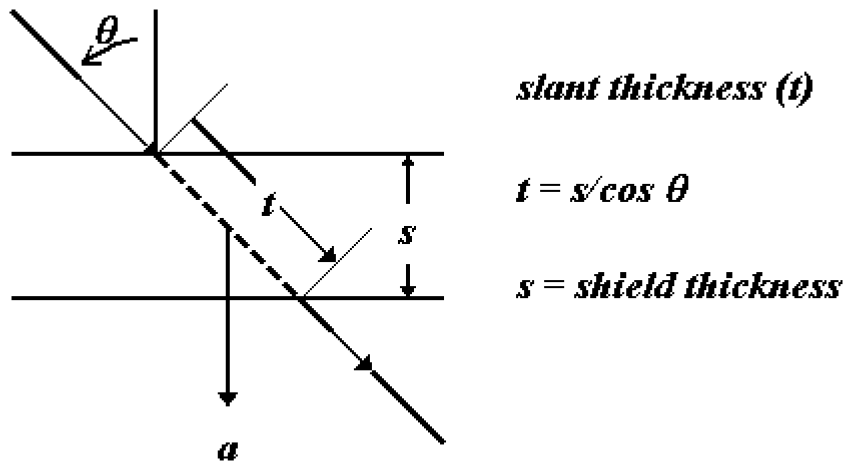

Lead or steel insert
30 cm
30 cm
Secondary shielding
Primary shielding
Isocenter
Target

Figure 3



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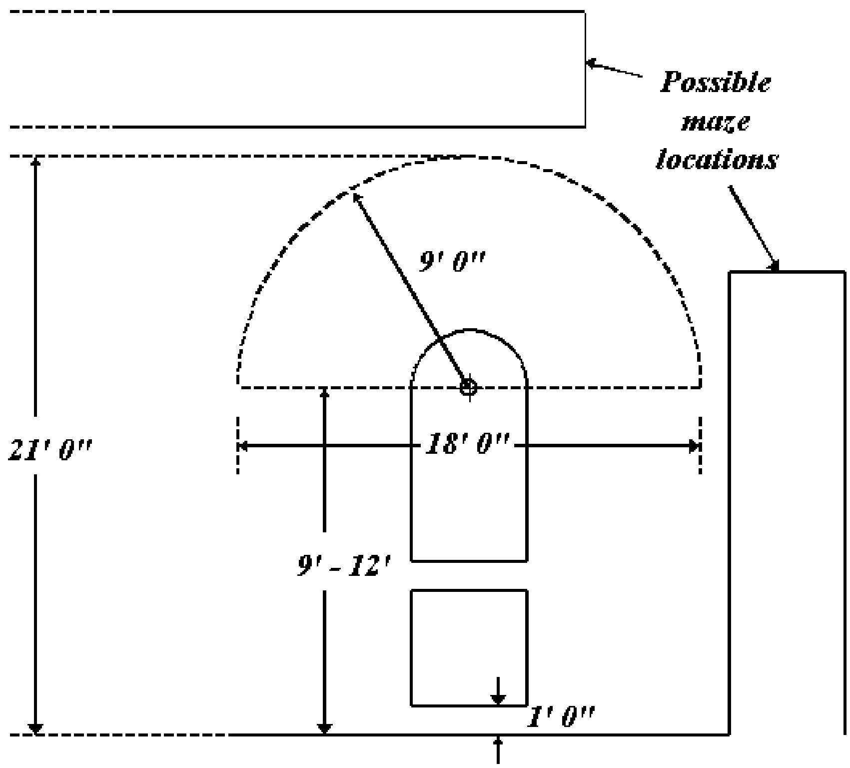

Figure 5

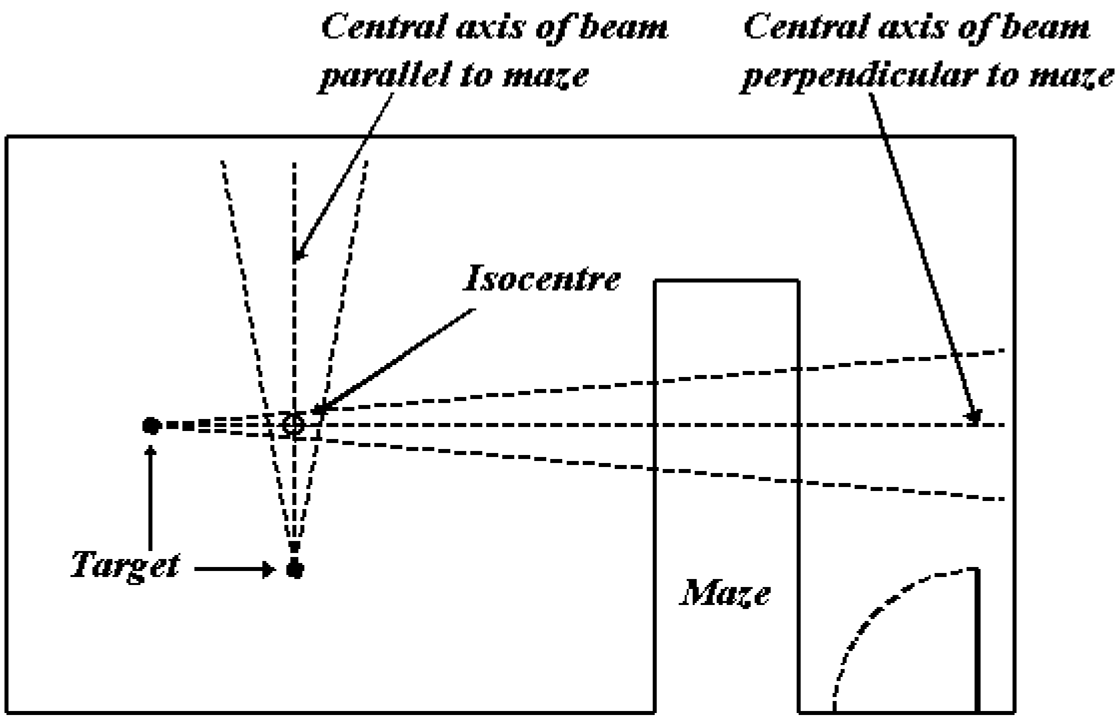
Central axis of beam
parallel to maze
Central axis of beam
perpendicular to maze
Isocentre
Target
Maze

Figure 6

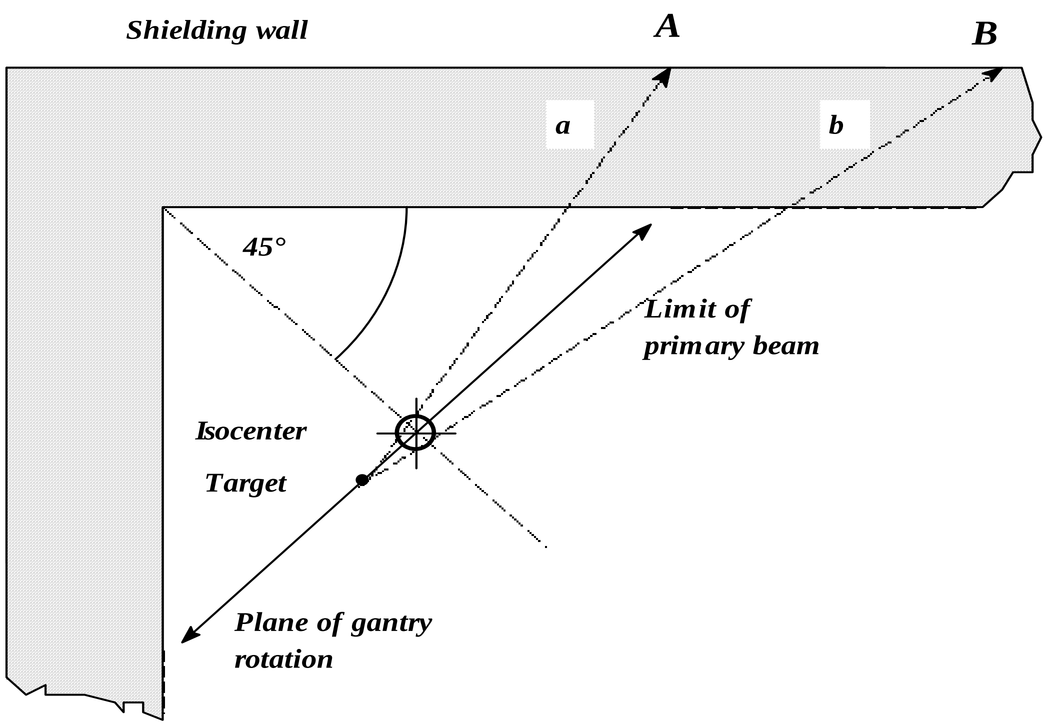
Shielding wall
A
B
a
b
45°
Limit of
primary beam
Isocenter
Target
Plane of gantry
rotation

Figure 7

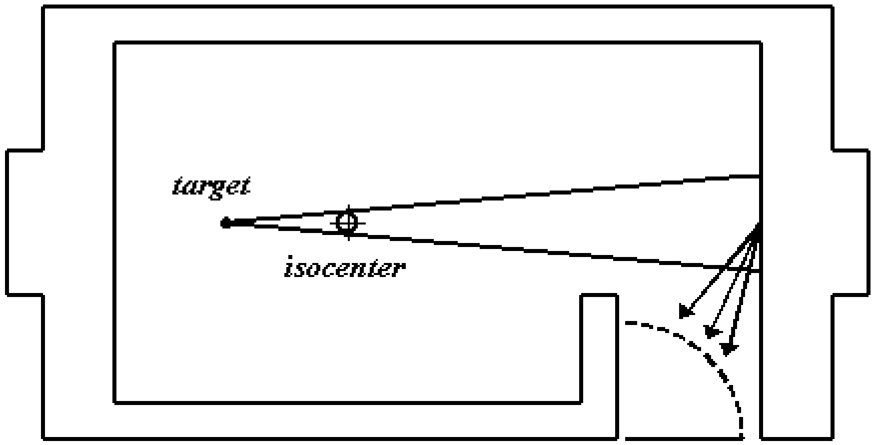

Figure 8

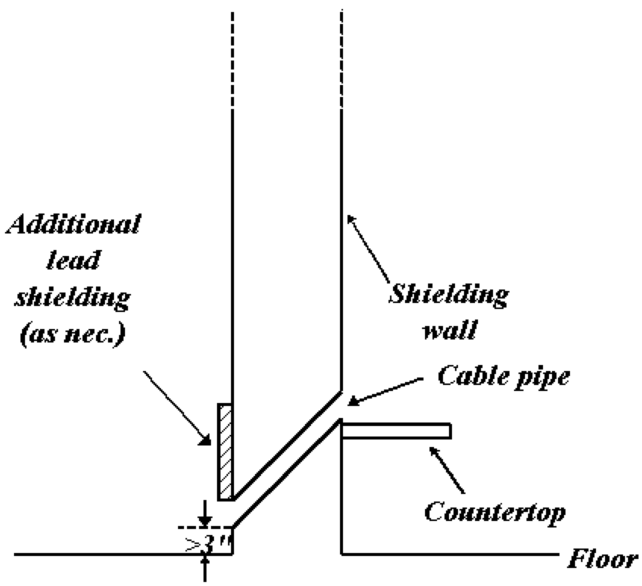
Additional
lead
shielding
(as nec.)
Shielding
wall
Cable pipe
Countertop
>3"
Floor

Figure 9

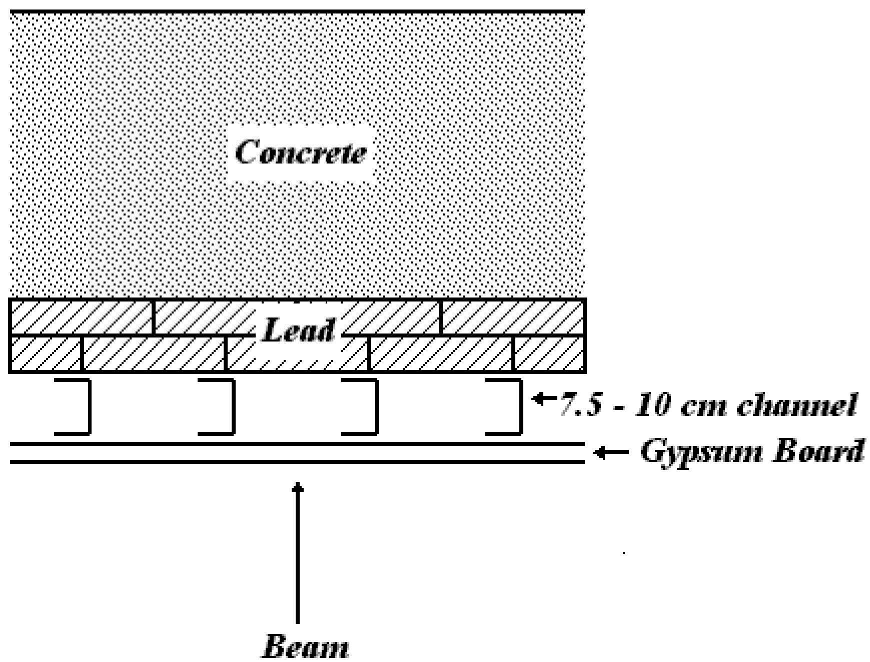

Figure 10

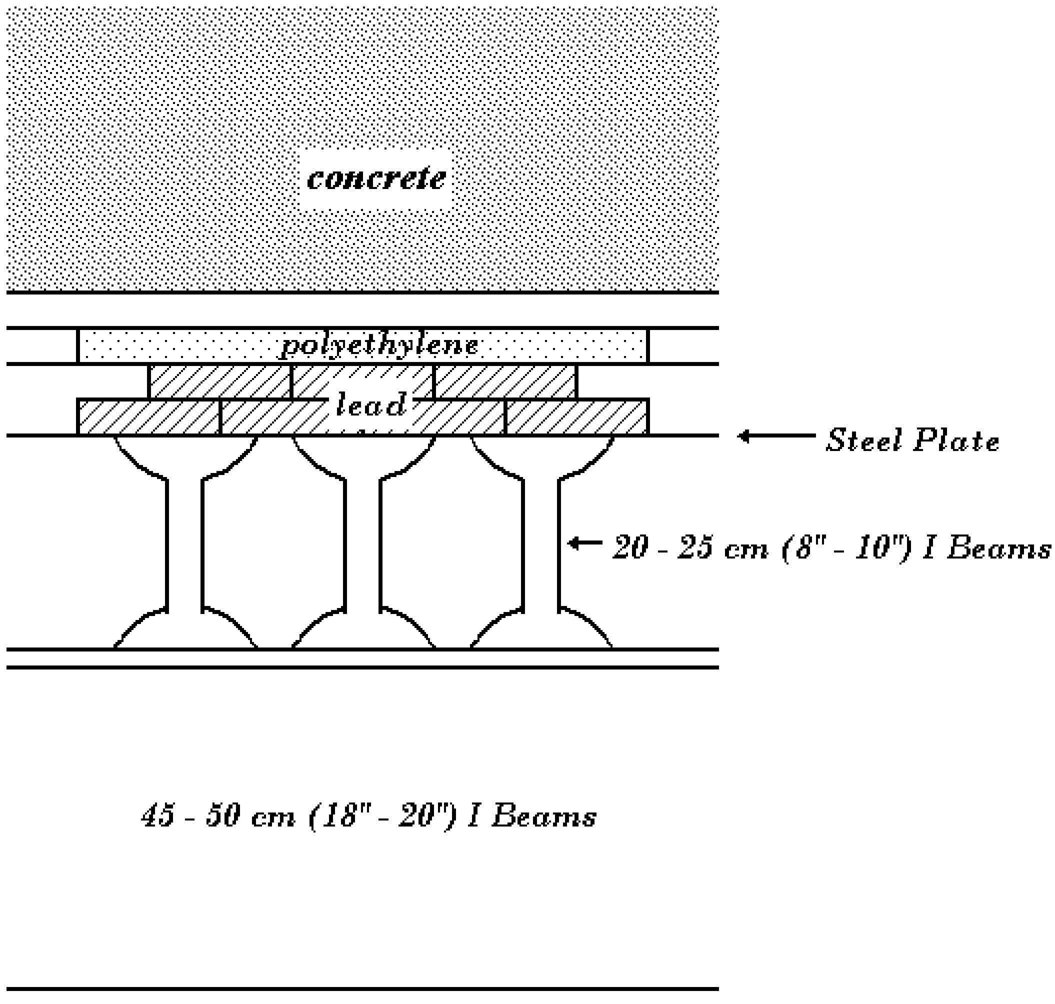
concrete
polyethylene
lead
Steel Plate
20 - 25 cm (8" - 10") I Beams
45 - 50 cm (18" - 20") I Beams

Figure 11

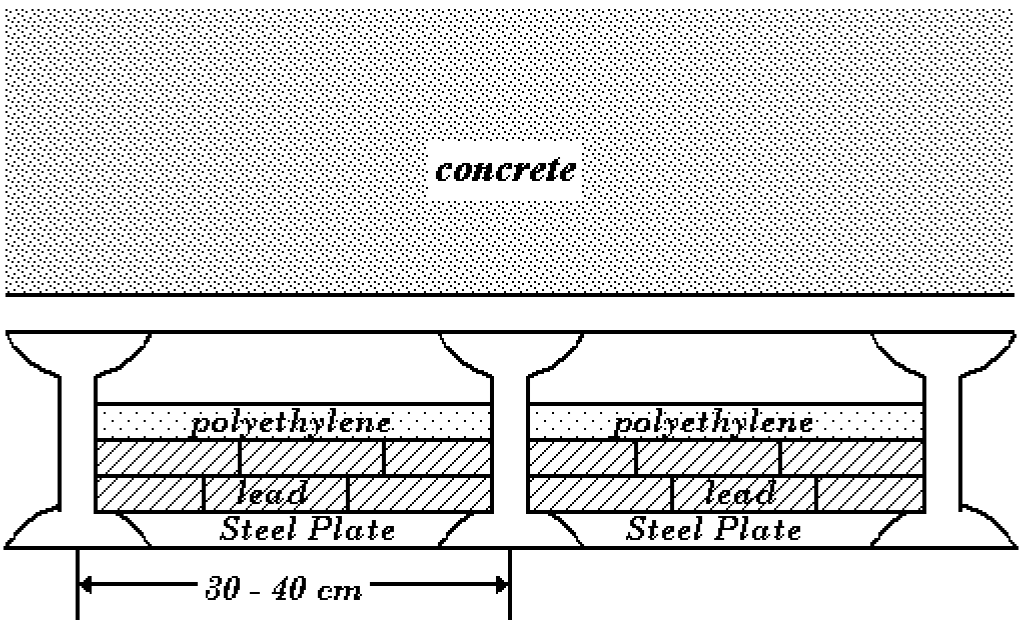
concrete
polyethylene
lead
Steel Plate
polyethylene
lead
Steel Plate
30 - 40 cm

Figure 12

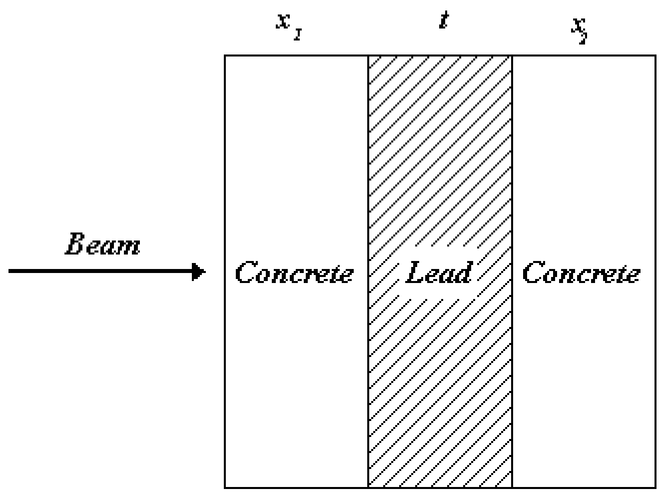

Figure 13

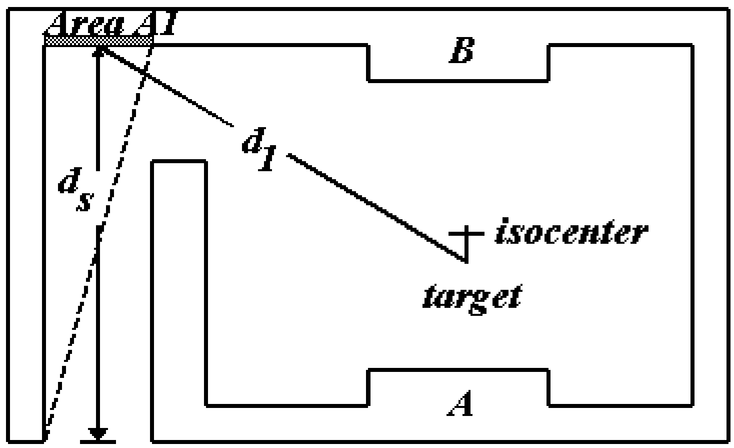

Figure 14

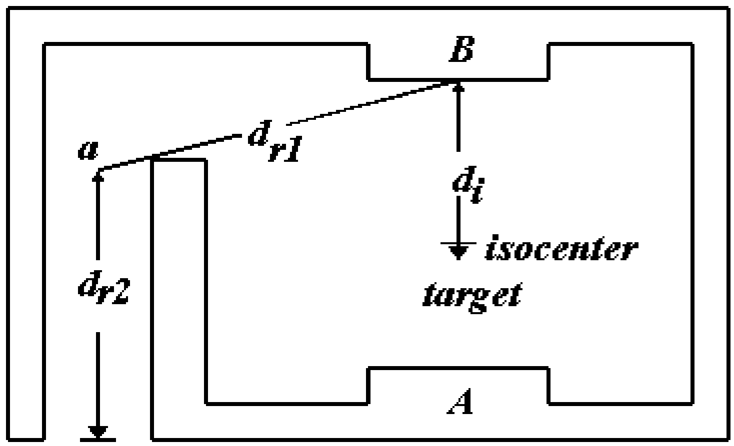

Figure 15

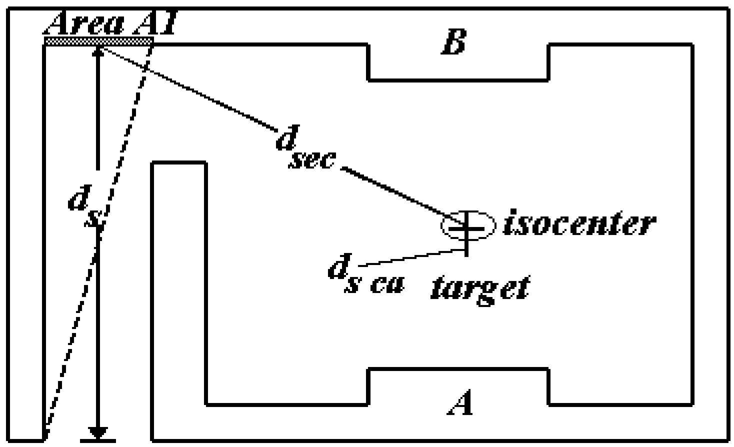

Figure 16

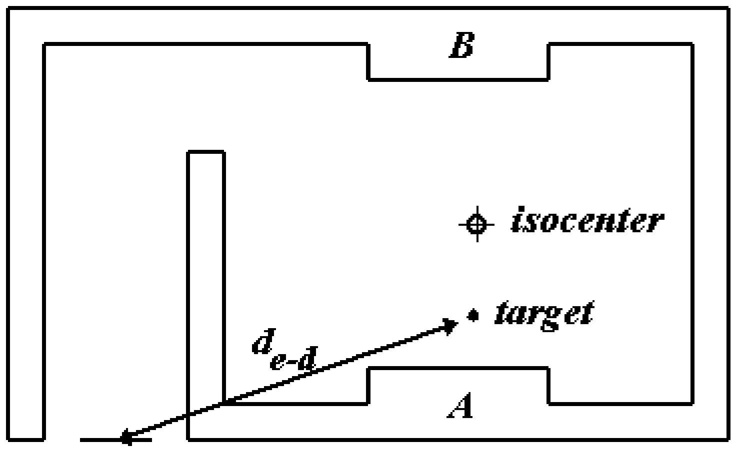

Figure 17

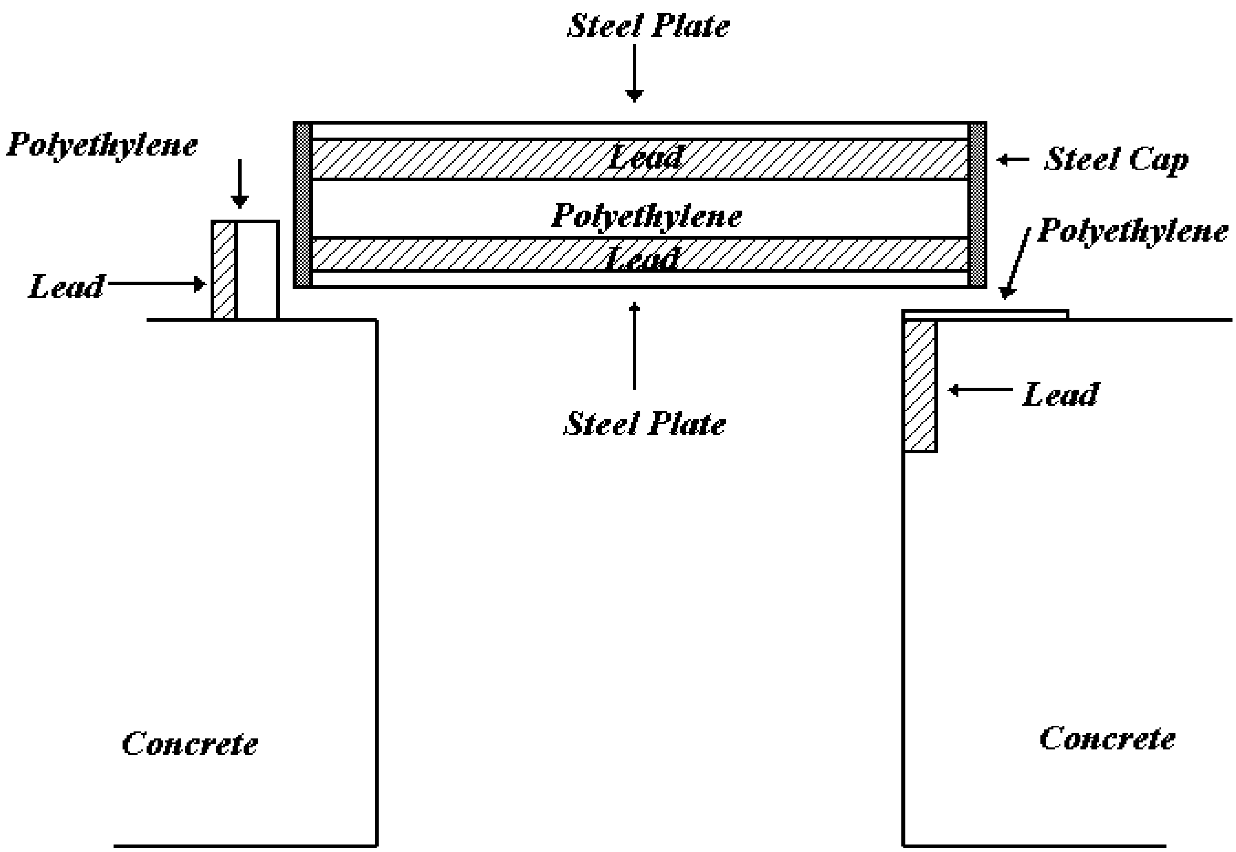
Steel Plate
Polyethylene
Lead
Steel Cap
Polyethylene
Polyethylene
Lead
Lead
Lead
Steel Plate
Concrete
Concrete

Figure 18

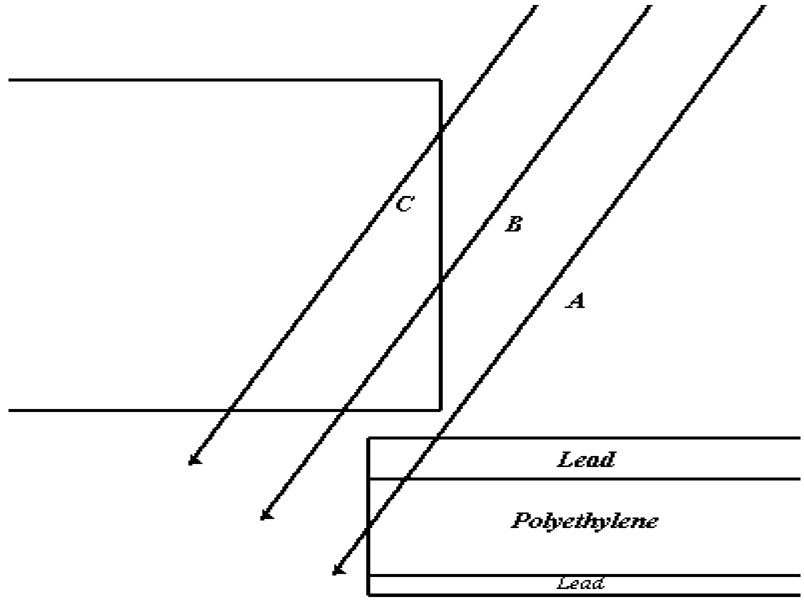

Figure 19

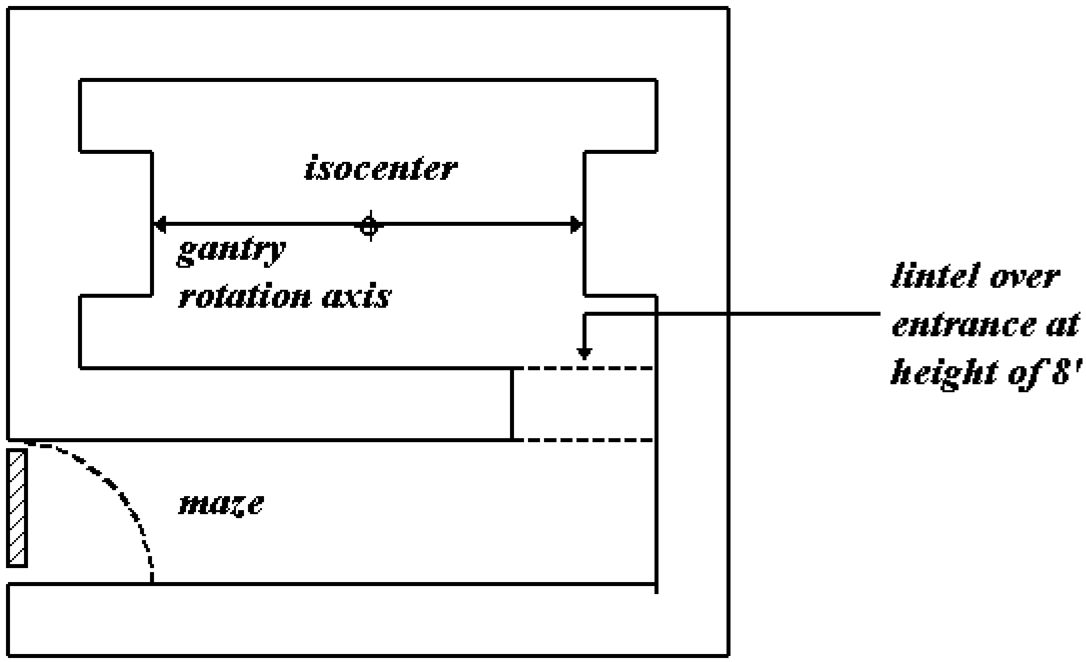
isocenter
gantry
rotation axis
lintel over
entrance at
height of 8'
maze

Figure 20

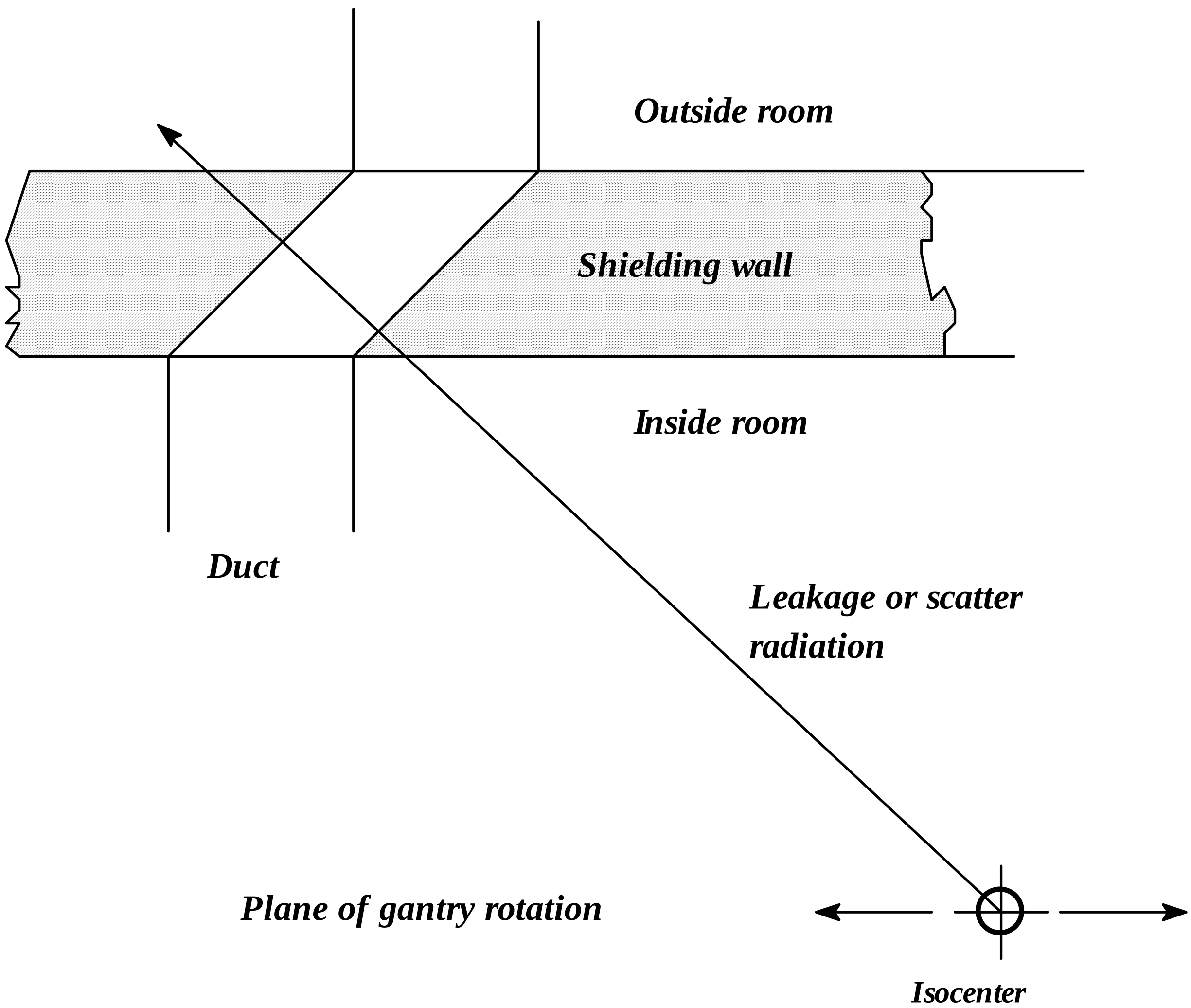
Outside room
Shielding wall
Inside room
Duct
Leakage or scatter radiation
Plane of gantry rotation
Isocenter

Figure 21

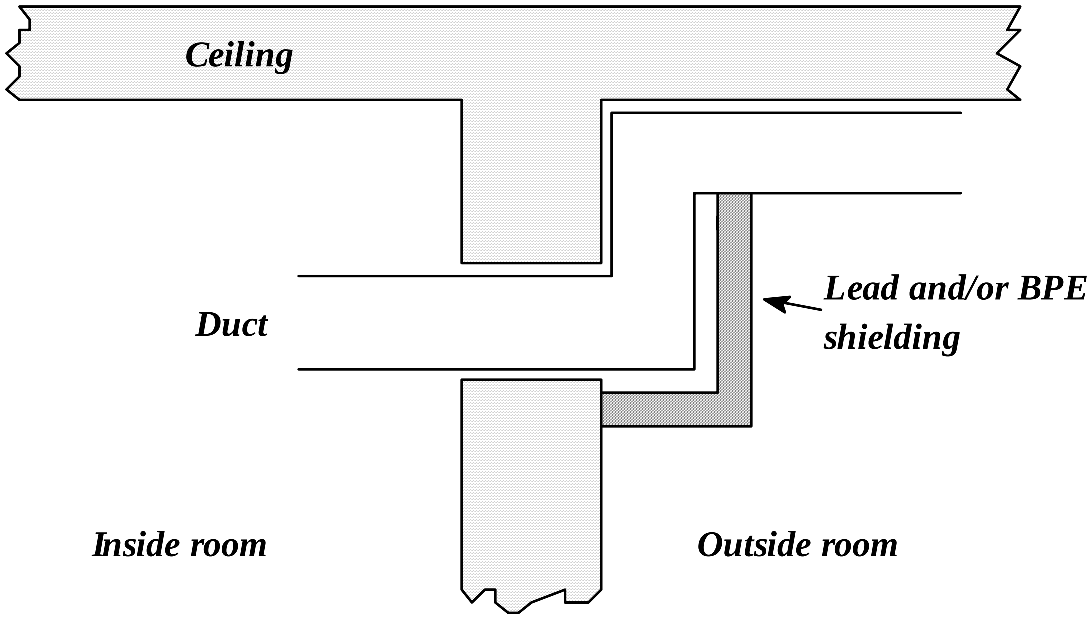
Ceiling
Duct
Lead and/or BPE shielding
Inside room
Outside room

Figure 22

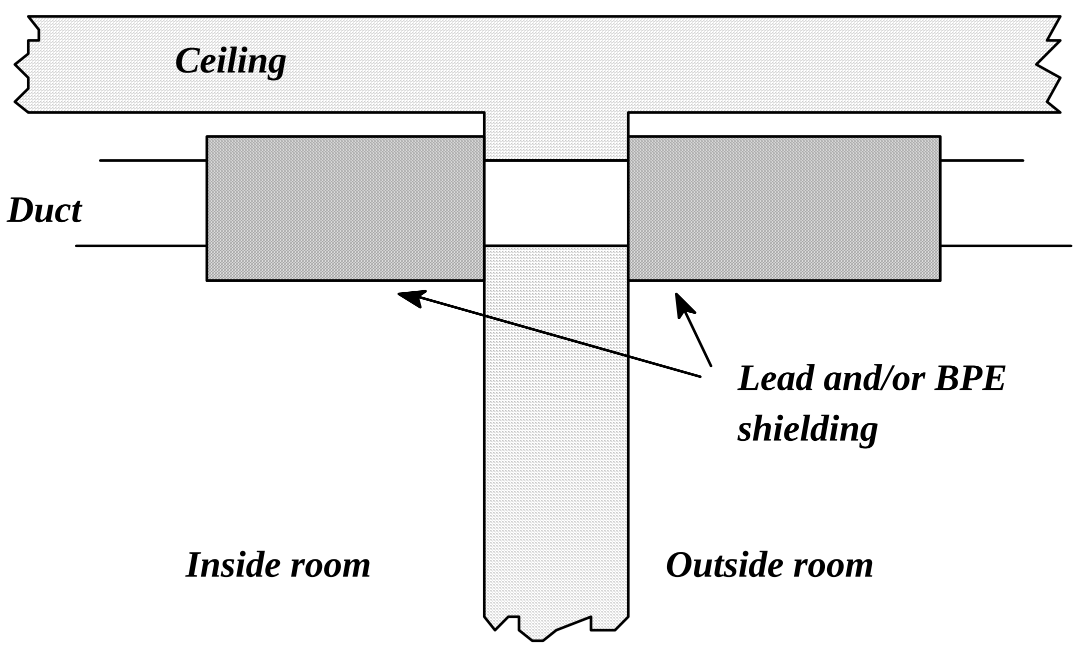
Ceiling
Duct
Lead and/or BPE shielding
Inside room
Outside room

Figure 23

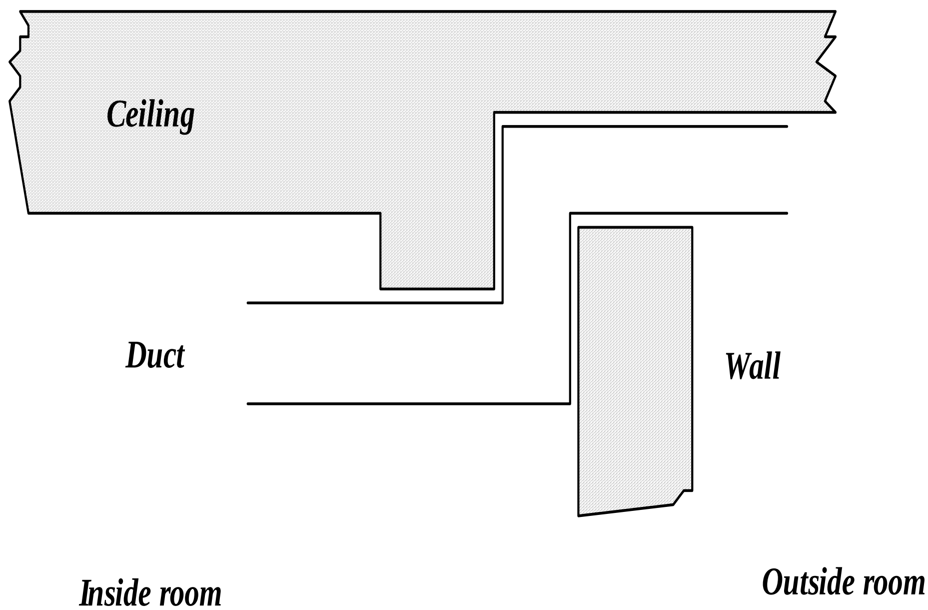

Figure 24

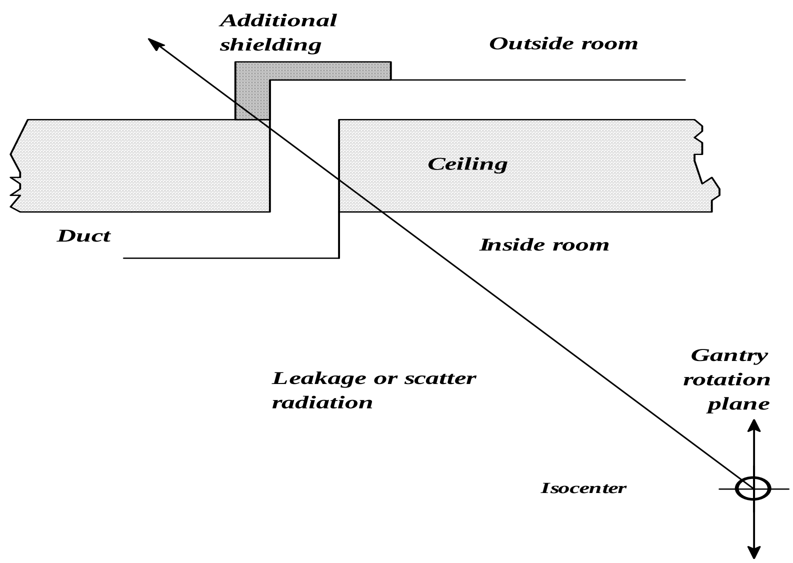
Additional
shielding
Outside room
Ceiling
Duct
Inside room
Gantry
rotation
plane
Leakage or scatter
radiation
Isocenter

Figure 25

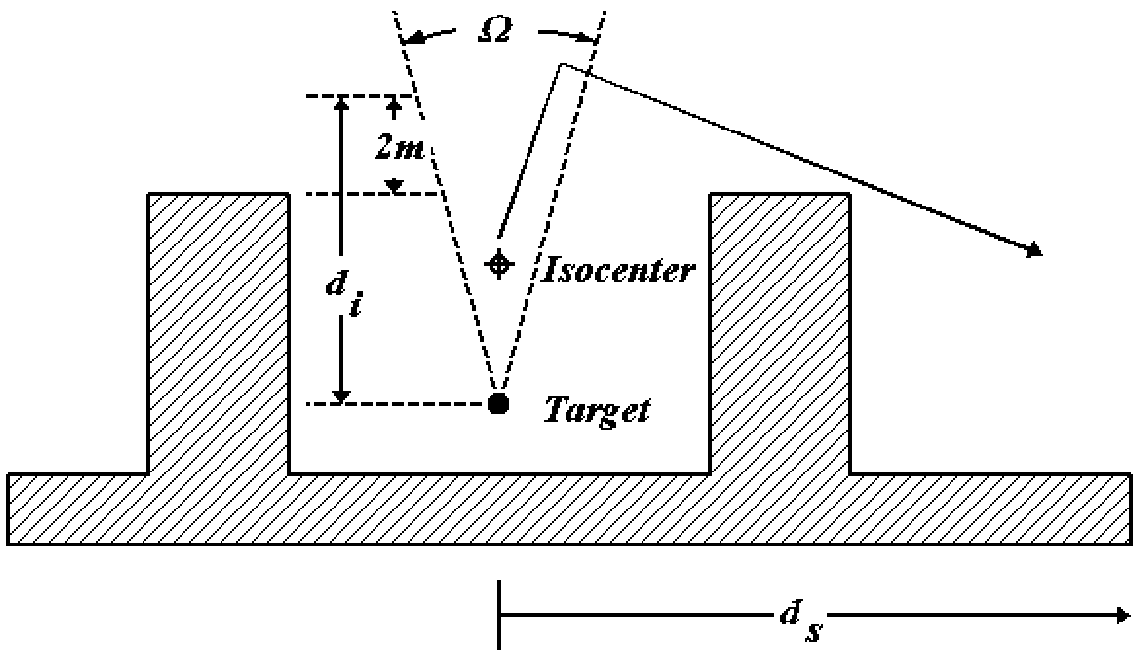

Figure 26

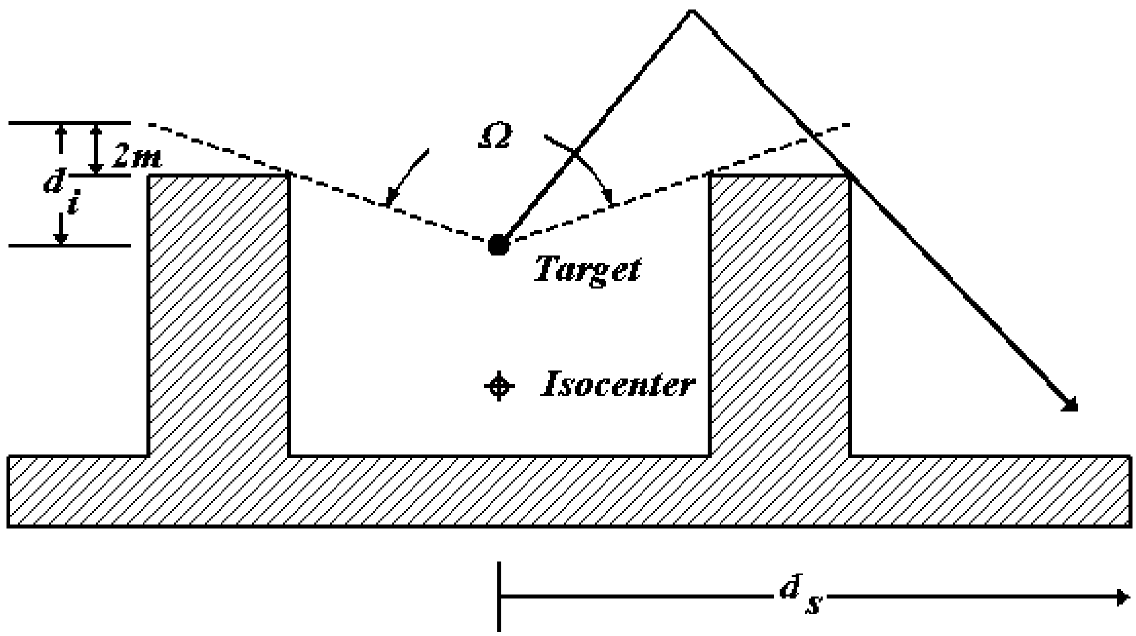

Figure 27