Chapter 15

Electron Accelerators: Shielding Aspects

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Owing to full operational controllability and uniqueness of treatment of product in their final stage of transportation / production, electron beam (EB) accelerators have achieved a massive popularity among the industries and researchers. Electron accelerators are used as radiation source to modify the characteristics of materials for various societal needs including food,agriculture, polymers, medical, semiconductors, exotic color enhancement of gems and many more. EB accelerator can be able to generate dose rate in range of kGy/min or more and therefore the radiation shielding aspects of accelerators are very crucial with reference to safety [41]. Basically when energetic electron hits any material, it generates X-rays also called bremsstrahlung. Since electron is charged particle with a finite mass and therefore it has a fixed range to travel in a particular material before stopping or conversion to another particle or photon. But the main challenge is X-ray photon which can move up to very long distance in material prior to achieving insignificance. There are two major events resulting in bremsstrahlung generation. One is intentional means that incidence of EB on target material eg iron, steel or some other high Z after acceleration. Another is EB loss during acceleration that concluded in interaction with accelerator structure materials leading to X-rays called leakage radiation. The shielding of all X-rays are equally important because those are categorized as hard X-ray. Additionally shielding of scattered X-rays, generated due to scattering of primary or leakage X-rays from the wall, floors, ceiling, structure materials etc, are also vital. Secondary barrier and maze type entry-exit are decided based upon scattered X-rays profile and intensity. It also resolves the thickness of ceiling and the design of S-bend for cabling and piping. In terms of industrial applications (other than medical) of electron accelerators the permissible energy is limited up to 10 MeV to avoid chance of neutron generation. Hence for these types analysis of neutron safety is not taken into account here. Thus the shielding compulsions of EB accelerators are dissimilar from radioactive source based irradiation facility to meet the goal of radiation safety. In the present chapter shielding estimation and its technical aspects related to high power EB accelerators have been elaborated for industrial uses.

15.1 Shielding of Electron Accelerators

The goal of radiation shield is to cut down the effective equivalent dose rate up to permissible level at point of interest having human occupancy. The permissible level of radiation is defined in two individual states for shielding estimations: (i) Uncontrolled area where the permissible limit is 20 μSv/week (or 0.5 μSv/h) and (ii) Controlled occupancy area (or radiation worker area) having the permissible limit is 200 μSv/week (or 5 μSv/h). In shielding estimations all factors, such as weekly workload of the accelerator, distance from point of generation, occupancy factor and beam directionality factor, are taken into account.

15.1.1 Shielding Estimations

The radiation generated by accelerators is divided into two components: (i) Main or Primary and (ii) Secondary. Scattered and leakage both jointly comprise the secondary radiation.

A. Primary shielding

Primary radiation is that generated in the beam line or front direction of the accelerated high energy electron beam. The primary shield transmission factor (B_P) is evaluated as:

$$B_P = \frac{Pd^2}{WUT} \tag{15.1}$$

Where P: allowed design dose limit per week for respective occupancy (Sv/wk);

d: distance of radiation generation point or source to the interest point (m);
W: workload per week (Gy/wk);
U: directionality factor (usually 1 for industrial accelerators);
T: occupancy factor.

B_P (shield transmission factor) is correlated with primary shielding thickness by number of Tenth Value Layers (TVLs) as

$$n = ln\left(\frac{1}{B_P}\right) \tag{15.2}$$

Thus the shielding thickness is decided by number of required TVLs. TVL depends upon the energy of X-rays generated by EB accelerators and shielding materials. First TVL (denoted as TVL_1) and subsequent TVLs (TVL_e) may not be the same. Therefore in general the desired primary barrier thickness is represented as

$$t = TVL_1 + (n-1)TVL_e \tag{15.3}$$

B. Secondary shielding

(i) **Scatter radiation:** This is originated as result of scattering of primary beam from the front line barrier or the material to be irradiated. The scattered barrier transmission factor (B_s) is:

$$B_s = \frac{Pd_{sca}^2 d_{sec}^2}{\alpha WT}\left(\frac{400}{F}\right) \tag{15.4}$$

Where F: scatterer area in the beam plane (cm^2);
α: scattering factor, also known as albedo factor, decided by beam energy;
d_{sca}: scatterer to the source of radiation distance (m);
d_{sce}: scatterer to the point of interest distance (m).

The secondary barrier thickness can be concluded from B_s with following relation

$$t = TVL_s log\left(\frac{1}{B_s}\right) \tag{15.5}$$

TVLs: Tenth value layer of scattered radiation led by primary beam energy. Additionally the energy decides the albedo factor and mentioned in references [73–76].

(ii) **Leakage radiation:** It causes due to interaction of primary electrons with structural components of accelerator such as cavity, beam tubes, magnet, collimator, horn etc. It is generated in the accelerator vicinity only. The leakage shield transmission factor (B_L) is given as:

$$B_L = \frac{Pd_L^2}{10^{-3}WT} \tag{15.6}$$

Where d_L: distance from the source (or the accelerator) to the interest point (m).

As per regulatory guideline the allowed leakage radiation level is 0.1 % of the primary beam at 1 m, also called source term, and therefore factor 10^{-3} has been introduced. The shielding thickness can be decided from B_L with given relation

$$t = TVL_L log\left(\frac{1}{B_L}\right) \tag{15.7}$$

TVL_L: Leakage radiation tenth value layer depending upon primary beam energy.

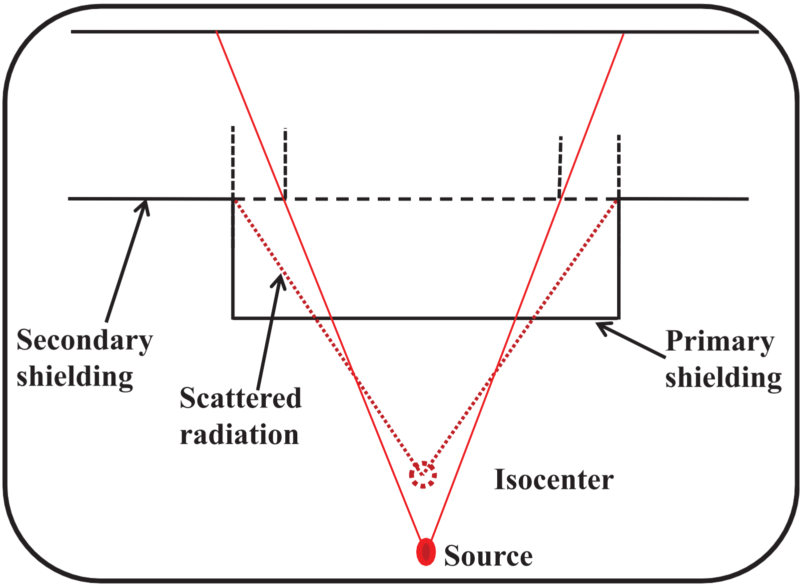

Figure 15.1: Schematic of primary and secondary shielding in beam direction.

It is important to note that while estimating primary barrier thickness the impact of secondary radiation need not to be taken into account. But for secondary shielding barrier, such as side walls, ceiling, maze walls etc, both the scattered and leakage radiations must be considered. Fig. 15.1 depicts the primary and secondary shielding in beam direction.

C. Skyshine

Skyshine is generated because of insufficient ceiling shield to attenuate the primary beam when it points directly or angularly in upwards direction. The reflection from deep atmospheric layers reasons the skyshine radiation, as depicted in Fig. 15.2. In order to quantify the skyshine shielding thickness, ceiling shield transmission factor (B_{xs}) can be introduced as [77–79].

$$B_{xs} = \frac{P d_{\nu}^2 d_h^2}{2.5 \times 10^{-2} W \Omega^{1.3}} \tag{15.8}$$

Where P: Allowed radiation level per week at distance beyond d_h (Sv/week);
Ω: Solid angle of the beam (steradian);
d_{ν}: Vertical distance from the X-ray source to a point 2 m above the roof (m);
d_h: Horizontal distance of point of interest from the X-ray source (m);
W: Weekly workload generated at 1 m from the X-ray source (Gy/week).

The roof thickness can be deduced from B_{xs} with the following relation

$$t = TVL_L log\left(\frac{1}{B_{xs}}\right) \tag{15.9}$$

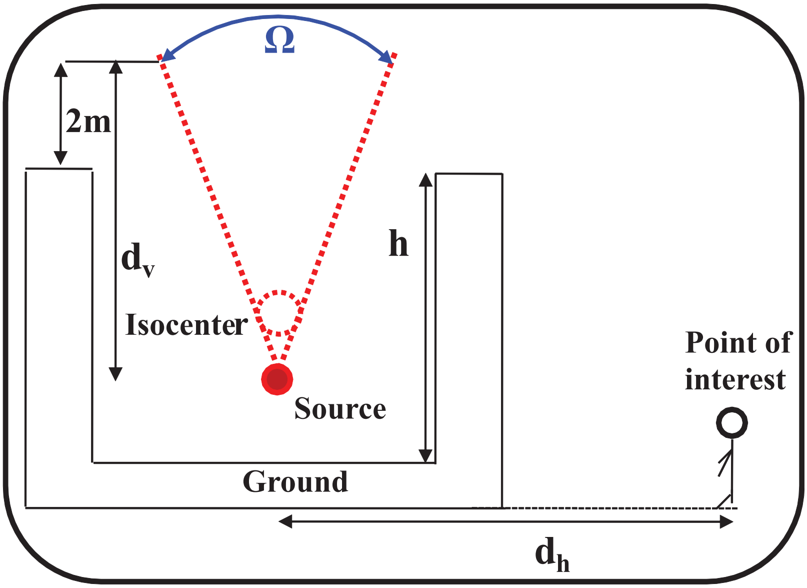

Figure 15.2: Sketch showing the parameters used for skyshine radiation.

15.1.2 Workload, Use Factor and Occupancy Factors

A. Workload

Workload is basically the radiation level generated by the machine per unit time at a meter distance in beam direction and is also defined as source term. As per convention the workload is denoted in weekly basis (as 'Gy/week') which can be achieved by multiplying dose per hour with number of machine operation hours per week. For example an accelerator for radiography applications having source term 2 Gy/min at 1 m and it radiographs 100 similar items per day taking 1 minute for one item and operational for 6 days in a week, its workload (W) is 1200 Gy/week.

If a machine can provide two or more energies by setting the parameters accordingly, then the point arises that which energy is to be apportioned to consider source term. For such cases, it is better to be conservative and assuming all the operation with respect to highest energy to fix the workload related to shielding analysis and design unless it is exclusively documented for mixed energy contributions.

B. Occupancy Factor

The occupancy factor for a shielding barrier is correlated with the maximum time elapsed by a person in the vicinity beyond that particular shielding barrier. In case of uncontrolled areas three specific fractional values have been assigned [73]. One is full occupancy area having occupancy factor one and locations come under this are living quarters, offices, laboratories, staff stations and nearby buildings with occupancy. Second is quarter occupancy areas, having occupancy factor 1/4, applies to elevators for operators use, rest rooms, unattended parking regions and corridors. Third is one-sixteenth occupancy areas with value 1/16, designated to stairs, waiting rooms, toilets, unattended elevators, outside areas used for pedestrians or vehicular traffic. However for controlled areas, the occupancy factor is assigned to be unity means full time occupancy.

C. Use Factor

The use factor is associated with the time fraction over a span of one year in which the primary beam is directed towards a particular shielding barrier. It has been recommended that use factor for walls and ceiling is 1/4 and for floor is 1 [73]. Generally there is no occupied space beneath the room and hence the factor for floor is debatable. Alternatively if an occupied space exists below the floor, 1/4 use factor should be considered. It is interesting that normally the primary beam direction is unchangeable for all accelerators, except medical accelerators, leading to fixed use factor.

15.1.3 Shielding Materials

Radiation shielding goal of accelerators is achieved with different materials or their appropriate combinations, however some typical shielding materials are extensively used for the same [76]. The selection of materials is governed by many factors including electron beam energy, site availability, types of applications, budget etc.

A. Lead

Lead is used as shielding material as having advantage of high atomic number and density (11350 kg/m^3) leading to very low TVL values. Thus it is highly suitable for the cases in which space constraints is the major factor. Also lead as shielding is common pertinent for self shielded as well as low energy accelerators (energy up to 0.8 MeV). One limitation with lead is of sagging nature i.e. not self supporting. To overcome it needs to be held in place with steel or mixed with antimony. Ducts, S-bends etc are the prime source of leakage radiation or hot spots which must be sealed with appropriate shield. For such cases interlocking type lead bricks are extremely advantageous to stop the leakage radiation. Lead is relatively transparent to neutrons which is a major drawback associated with it.

B. Steel

Steel is prime shielding material of density 7850 kg/m^3 and it is broadly suitable for space limiting conditions. It has rigid characteristics but despite that it needs external support. It is advantageous as laminated shielding for primary barriers compared with lead, since it produces fewer photo-neutrons [80].

C. Concrete

Concrete is the most suitable candidate for high energy accelerators (> 6 MeV) and inexpensive quality makes it advantageous over counterparts [80]. It is also takes care of neutrons along with X-rays for accelerators having energy greater than 10 MeV. The standard density of concrete is 2350 kg/m^3 and if the actual density varies, the TVLs should be adjusted accordingly. Other types of concretes can also be fabricated like of density 3700 kg/m^3 by adding iron as aggregate in the concrete.

D. Earth

Soil (or dry packed earth) is a useful and quite inexpensive shielding material of density around 1160 kg/m^3. It is convenient to construct vaults in underground locations because of presence of the natural shielding as walls.

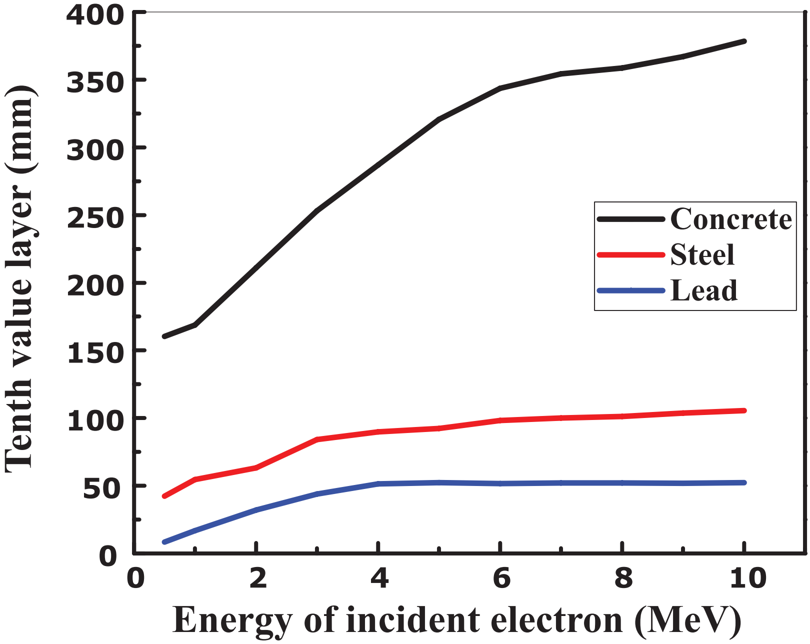

Figure 15.3: Monte Carlo simulation generated tenth value layer for X-ray shield as function of incident electron energy for different materials.

15.2 Tenth Value Thicknesses (TVTs)

The thickness of shielding material diminishing the transverse radiation intensity by 10 times of incident intensity is termed as tenth value thickness (TVT) or tenth value layer (TVL). It depends upon energy of radiation as well as kind of material. Monte Carlo simulation generated TVLs for X-rays radiation, of different materials, with respect to incident electron beam energy, is presented in Fig. 15.3. Additionally TVLs of some common shielding materials for primary X-rays as function of spectrum end point energy, are given in table 15.1 [77]. The TVLs for leakage radiation depend strongly on the angle of the radiation relative to the primary beam axis. The TVL values fall with increase in angle from front to the backward direction for beam energy above 1 MeV [78]. Typical TVLs for leakage radiation, for different materials, of separate X-ray spectrum end point energy are shown in table 15.2.

The TVL for scattered radiation of concrete are 179 mm up to 6 MV X-ray and 198 mm for 6-10 MV.

Table 15.1: TVL values for different X-ray energies; first TVL / subsequent TVLs [63].

Energy (MV)	Concrete (mm)	Steel (mm)	Lead (mm)
1	180 / 150	57 / 54	11 / 25
3	260	88 / 82	46 / 48
4	280	90	51 / 53
6	345	100	52
10	380	104	52

Table 15.2: Leakage TVL values for different X-ray energies [63].

Energy (MV)	**Concrete (mm)**	**Steel (mm)**	**Lead (mm)**
3	212	70	40
6	279	85	44
10	305	82	46

15.3 Conclusions

In order to ensure the radiation safety and economical aspects, the shielding estimation techniques have been elaborated with suitable shielding material options. Accelerator facility has to satisfy the two eminent obligatory standards dosimetry and shielding. The present chapter may also be advantageous to establish a new accelerator facility to attain the desired goal of industry as well as research institutions.