

# RADIATION SHIELDING AND BARRIER

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## 16.1. INTRODUCTION

The advent of diagnostic radiology has revolutionized the field of medicine by enabling non-invasive visualization of the internal structures of the human body. From conventional X-rays and computed tomography (CT) scans to more specialized modalities like fluoroscopy and interventional radiology, the applications of diagnostic imaging have significantly enhanced clinicians' ability to diagnose, monitor, and manage a myriad of medical conditions. However, the same ionizing radiation that provides these clinical benefits also carries inherent biological risks <sup>[1]</sup>. These risks arise from the interaction of ionizing radiation with living tissues, which can lead to cellular damage, genetic mutations, and, in some cases, the development of cancer. Consequently, the importance of radiation protection cannot be overstated. One of the primary methods of mitigating the harmful effects of radiation exposure in medical settings is through effective radiation shielding. Radiation protection shielding is the practice of using physical barriers to absorb or deflect ionizing radiation, thereby reducing exposure to healthcare workers, patients, and the public. The concept is rooted in fundamental principles of radiological protection established by various international regulatory bodies, such as the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and the International Atomic Energy Agency (IAEA). These organizations have emphasized a framework that includes three main pillars of radiation protection: justification of exposure, optimization of protection (commonly known as the ALARA principle—As Low As Reasonably Achievable), and dose limitation. Shielding falls primarily under the second pillar and plays a pivotal role in optimizing protection during diagnostic procedures <sup>[2]</sup>.

In diagnostic radiology, shielding is designed to attenuate primary and scattered radiation emitted during imaging procedures. Primary radiation refers to the direct beam of X-rays produced by the X-ray tube, whereas scattered radiation is generated when the primary beam interacts with the patient's body or other objects in the room, leading to deflected rays in various directions. Scattered radiation poses a particular challenge because it contributes significantly to the dose received by medical personnel and can affect adjacent patients or even the public if adequate shielding is not in place. Therefore, designing and implementing shielding measures involves not only absorbing the intense primary beam but also accounting for the omnidirectional and lower-energy scatter that can permeate walls, ceilings, floors, and other structural elements <sup>[3]</sup>. The need for radiation shielding becomes particularly pronounced in environments where radiological equipment is used frequently or continuously, such as in radiology departments, emergency rooms, intensive care units, operating theatres, and specialized imaging centers. In these settings, cumulative radiation doses to personnel can quickly exceed recommended limits if proper shielding is not employed. Furthermore, shielding must be tailored to the specific characteristics of the

imaging modality being used. For instance, CT scans produce high doses of radiation over a short period, requiring thicker and denser shielding than conventional radiography. Fluoroscopy, on the other hand, involves prolonged exposure times and requires dynamic shielding solutions such as mobile lead barriers and protective garments. These distinctions underscore the necessity for a nuanced understanding of both the physics of radiation and the clinical requirements of diagnostic imaging.

Materials commonly used for radiation shielding include lead, concrete, barium, tungsten, and various composite and polymer-based alternatives. Each material offers different advantages in terms of density, cost, toxicity, structural properties, and ease of handling. Lead, due to its high atomic number and density, remains the gold standard in most shielding applications; however, its toxicity and weight present challenges in handling, installation, and disposal. As a result, alternatives such as lead-free garments, non-toxic composites, and even nanomaterials are increasingly being explored for use in both permanent and wearable shielding solutions. The selection of appropriate shielding material and thickness is a complex process influenced by multiple factors, including the energy spectrum of the X-rays, the workload of the imaging unit, distance from the radiation source, and occupancy of adjacent areas. From an architectural standpoint, shielding is integrated into the design of diagnostic imaging suites to ensure compliance with local and international safety standards. This involves the construction of lead-lined walls, doors, and windows, the installation of leaded glass for observation panels, and the strategic positioning of equipment to minimize unnecessary exposure. Specialized software tools and mathematical models are often employed during the design phase to simulate radiation fields and optimize the placement and thickness of shielding materials. Regular radiation safety audits and quality assurance protocols are essential to verify the integrity and effectiveness of shielding over time, especially in facilities with aging infrastructure or high utilization rates. Equally important is the role of personal protective equipment (PPE) in radiation shielding. Healthcare professionals who operate or assist in radiological procedures are typically required to wear lead aprons, thyroid shields, leaded gloves, and sometimes leaded eyewear. These items are designed to provide localized protection, especially in areas of the body most vulnerable to radiation-induced damage, such as the thyroid gland and reproductive organs. However, the effectiveness of PPE is contingent on proper usage, maintenance, and periodic testing for defects. Moreover, protective garments can be physically burdensome, contributing to fatigue and musculoskeletal issues over long shifts. The development of lighter, ergonomically designed, and equally effective protective wear is an ongoing focus of research and innovation in the field <sup>[4]</sup>.

The importance of shielding is not confined to healthcare workers; patients must also be protected, particularly when imaging children, pregnant women, or individuals undergoing repeated radiological examinations. Pediatric patients are especially sensitive to radiation due to their developing tissues and longer life expectancy, which increases the window for potential radiation-induced effects to manifest. In such cases, the use of pediatric-specific shielding, meticulous protocol optimization, and dose-tracking systems becomes essential. Shielding accessories like gonadal shields, breast shields, and collimators are routinely employed to limit exposure to non-target areas. Additionally, patient education and informed consent are critical components of ethical radiological practice, ensuring that individuals are aware of the benefits and risks associated with radiation exposure and the protective measures in place. Beyond clinical settings, radiation protection shielding also has implications for public health and regulatory compliance. National and international guidelines mandate that facilities using radiological equipment implement specific shielding requirements to prevent radiation exposure to people outside the imaging area. These requirements are enforced through licensing, inspections, and regular reporting by governmental health and safety authorities. Inadequate shielding or non-compliance can result in legal liabilities, financial penalties, and, most importantly, preventable harm to individuals <sup>[5]</sup>.

## **16.2. CLASSIFICATION OF RADIATION SHIELDING IN DIAGNOSTIC RADIOLOGY**

Radiation shielding in diagnostic radiology represents a fundamental element of radiation protection and is essential to minimize exposure to ionizing radiation for occupational workers, patients, and the general public. Shielding strategies are scientifically designed based on the type, intensity, and direction of radiation generated during diagnostic imaging procedures, primarily X-rays. The selection of shielding material and technique

depends on factors such as photon energy, workload, occupancy, distance, and the shielding location within the imaging environment. In clinical practice, shielding configurations are categorized into well-defined classes based on their function and placement within the radiological system. These include source shielding (shielding at the X-ray tube housing), structural shielding (fixed architectural barriers such as lead-lined walls, ceilings, doors), patient shielding (organ-specific protective devices), mobile or temporary shielding (portable barriers for non-protected environments), and personnel shielding (PPE worn by staff). Each category plays a unique and complementary role in achieving optimization of dose (ALARA principle), ensuring regulatory compliance, and maintaining safe operation in radiology departments.

### 16.2.1. Source Shielding

Source shielding is the first and most fundamental layer of radiation protection in diagnostic radiology, as it aims to confine ionizing radiation at the point of origin—within the X-ray generation system itself. The primary component responsible for this containment is the X-ray tube housing. This housing is manufactured with high atomic number (high-Z) materials such as lead, tungsten, or lead-equivalent alloys, which have high attenuation capabilities for diagnostic photon energies. The purpose of this housing is to absorb all unwanted radiation emitted in directions other than the collimated primary beam. International standards, such as those established by the International Electrotechnical Commission (IEC), mandate that leakage radiation from the tube housing must not exceed 1 mGy/hour at a distance of 1 meter when operated at maximum rated output. Compliance with this standard ensures the safety of radiographers and other nearby personnel even during high workload operation. Beam restriction devices form the second major component of source shielding. Collimators, typically constructed using lead shutter assemblies, are placed at the X-ray tube exit to define, shape, and limit the beam to the exact anatomical area of interest. By narrowing the beam geometry, collimation reduces both patient skin dose and secondary scattered radiation, thereby improving image quality and reducing occupational exposure.

Modern digital radiography systems incorporate automatic beam collimation linked to anatomical program settings, ensuring consistent field limitation practices <sup>[6]</sup>. In addition to physical containment, beam filtration is also considered part of source shielding. Filters, most commonly made of aluminum, copper, or K-edge filter materials are placed at the tube exit to selectively remove low-energy photons that contribute to patient surface dose without improving image formation. Current safety standards require a minimum total filtration of at least 2.5 mm aluminum equivalent for tube potentials above 70 kVp in general radiography. Some manufacturers add compound or spectral-shaping filtration to further reduce patient dose while maintaining optimal beam quality. Thus, source shielding integrates tube housing, collimation, and filtration as synergistic components that collectively minimize unnecessary radiation at its point of generation, thereby ensuring both patient safety and occupational radiation protection in clinical radiology practice.

### 16.2.2. Structural Shielding

Structural shielding forms the permanent architectural defense mechanism against radiation transmission in diagnostic radiology facilities. It is incorporated into the physical design and construction of imaging rooms and includes lead-lined walls, ceilings, floors, control room viewing windows, and entry doors. The selection and thickness of shielding materials are scientifically calculated based on multiple parameters such as X-ray tube workload (mA-min/week), operating peak tube potential (kVp), distance from the radiation source, occupancy factor of adjacent spaces (e.g., offices, waiting areas, public corridors), use factor (probability of beam direction), and permissible dose limits defined by regulatory agencies. Structural shielding is classified into two major categories: primary barriers and secondary barriers. Primary barriers are positioned in the direct line of the primary X-ray beam and are designed to attenuate high-intensity primary photons; they usually require higher lead equivalence or thicker materials such as lead sheets (commonly 1.5–2.0 mm Pb equivalent) or high-density concrete. In contrast, secondary barriers are installed to attenuate scattered radiation from the patient and leakage radiation from the X-ray tube housing, and typically require relatively lower shielding thickness (e.g., 0.5–1.0 mm Pb equivalent or concrete walls  $\geq 25$  cm depending on beam energy). Materials used for structural shielding include pure lead sheets, lead-based plaster boards, barium sulfate plaster, high-density concrete, steel panels, or

lead glass for observation windows. Each material is selected based on cost, installation feasibility, and required attenuation efficiency. The entire shielding design must comply with national and international standards such as NCRP Reports (e.g., NCRP 147), ICRP recommendations, and country-specific regulatory guidelines (e.g., AERB in India, FDA in USA). Periodic radiation surveys and quality assurance testing are mandated to verify that shielding integrity remains within acceptable tolerance limits after installation and during operation. Therefore, structural shielding acts as a critical and irreplaceable element of radiation protection, ensuring that workers, patients, and the general public occupying adjacent areas remain safely below annual dose constraints throughout the lifetime of the radiological facility.

### 16.2.3. Patient Shielding

Patient shielding refers to the use of specially designed protective devices that reduce radiation dose to sensitive organs or tissues which are not directly involved in the diagnostic examination. The main purpose of patient shielding is to minimize unnecessary exposure, especially to radiosensitive structures such as the gonads, thyroid gland, breast tissue, and the lens of the eye. This practice is particularly important in pediatric radiology, pregnant patients, repeated follow-up examinations, and higher dose modalities like computed tomography (CT) and fluoroscopy, where cumulative radiation dose may be significant. Patient shielding is implemented using a variety of lead or lead-equivalent accessories, including gonadal shields, thyroid collars, breast shields, eye shields, and abdominal or pelvic aprons. Gonadal shields have historically been one of the most common protective measures, especially in pelvic imaging of children and young adults, due to the higher risk of genetic effects from radiation to reproductive organs. However, modern evidence-based guidelines from organizations such as the American Association of Physicists in Medicine (AAPM) have recommended reduced routine use of gonadal shielding because misplacement can interfere with Automatic Exposure Control (AEC) systems, potentially increasing tube current (mA) and inadvertently increasing patient dose. Furthermore, poorly positioned shields can obscure anatomical structures, leading to repeat exposures.

Despite these revisions in practice, selective patient shielding remains clinically valuable when applied correctly—particularly for shielding the thyroid during head and neck examinations, and shielding breast tissue in young women undergoing CT chest imaging. Thyroid collars with 0.5 mm Pb equivalence are commonly used in dental radiography and fluoroscopy due to the thyroid's high radiosensitivity. Bismuth breast shields can reduce breast radiation dose by up to 30–40% in CT examinations when properly positioned after the scout image acquisition to avoid altering AEC modulation. Eye lens protection, using leaded eyewear or shields, helps reduce risk of radiation-induced cataract formation, especially in orbital imaging. Thus, patient shielding continues to play an important role in radiation protection, but its application must be based on current scientific evidence, proper placement technique, and understanding of imaging technology to ensure that the intended dose reduction is achieved without compromising diagnostic accuracy.

### 16.2.4. Mobile and Temporary Shielding

In diagnostic radiology, particularly in mobile and non-traditional imaging environments, mobile or temporary shielding plays a vital role in maintaining radiation safety standards where fixed structural shielding is either impractical or absent. This form of shielding is particularly essential in dynamic clinical settings such as operating theatres, emergency departments, intensive care units (ICUs), and bedside radiography in general hospital wards. In these scenarios, the infrastructure typically lacks the permanent, lead-lined walls and designated control rooms found in conventional radiology suites. Consequently, portable shielding devices are employed to provide a flexible, deployable layer of protection for both patients and healthcare workers. Mobile shields are engineered as portable panels, often mounted on wheels for ease of movement and repositioning. These panels are typically constructed with an internal core of lead sheet, ranging in thickness from 1.0 mm to 2.0 mm lead equivalence, sufficient to attenuate scattered X-rays and, to some extent, lower-energy primary radiation. The outer surface is usually covered with durable materials such as stainless steel or polymer laminates to facilitate disinfection and withstand routine wear and tear. Some mobile shields are also equipped with leaded glass windows, which allow clinicians to maintain visual contact with the patient without compromising on safety. These windows are

constructed using lead-barium or lead-silicate glass, offering protective equivalency typically in the range of 0.5 mm to 1.0 mm Pb, depending on thickness and manufacturer specifications.

The effectiveness of mobile shielding is highly dependent on correct positioning. Shields must be strategically placed between the radiation source and personnel, ideally at right angles to the beam path to intercept the maximum amount of scattered radiation. Common clinical practices involve positioning the mobile barrier adjacent to the patient's bed during bedside chest X-rays, or next to the fluoroscopic unit in an operating theatre. In many cases, mobile shielding is used in combination with personal protective equipment (PPE), such as lead aprons, thyroid collars, and leaded eyewear, to create a layered defense system against radiation exposure. This is particularly important during prolonged procedures like fluoroscopy-guided interventions, where the cumulative dose to staff can be significant. In addition to standard mobile panels, foldable or retractable shields are also available for environments with limited space or for procedures requiring rapid room turnover. These may include accordion-style leaded curtains or rolling partitions that can be deployed and stored easily. Some facilities also utilize ceiling-suspended mobile shields in hybrid operating rooms, which offer enhanced maneuverability and greater coverage in complex interventional procedures. Despite their versatility, mobile shields do have limitations. They generally provide protection against scatter radiation rather than the full intensity of the primary beam, and their effectiveness diminishes if improperly positioned or if the radiation source moves during the procedure. Therefore, radiation safety training is crucial to ensure that operators and supporting staff understand the principles of optimal shielding use and beam geometry.

### 16.2.5. Personnel Shielding

In diagnostic and interventional radiology, personnel shielding represents a critical aspect of radiation protection programs aimed at minimizing occupational exposure to ionizing radiation. This form of shielding involves the use of wearable protective devices—also known as personal protective equipment (PPE)—that are specifically designed to attenuate scattered or secondary radiation, which poses the greatest risk to healthcare professionals operating in or near X-ray environments. Personnel shielding is particularly essential in high-exposure settings such as fluoroscopy, interventional radiology, cardiac catheterization laboratories, and operating rooms, where medical staff often remain in close proximity to the radiation source for extended periods. The lead apron is the most commonly used form of personnel shielding. These garments are constructed with layers of lead-impregnated rubber or modern lead-free composite materials, and are available in a range of lead equivalences, typically from 0.25 mm to 0.5 mm Pb equivalent. The effectiveness of these aprons depends on their thickness and the energy of the X-ray beam; for instance, a 0.5 mm lead apron can attenuate approximately 90–95% of scattered X-rays at 100 kVp, providing substantial protection to the torso and vital organs. There are various styles of aprons, including front-only, full-wrap, and skirt-vest designs, each tailored for specific clinical settings and ergonomic comfort. Full-wrap designs offer superior protection, particularly for staff facing multidirectional scatter fields, whereas skirt-vest combinations help distribute weight and reduce musculoskeletal strain during long procedures<sup>[9]</sup>.

Another essential component of personnel shielding is the thyroid collar or thyroid shield. The thyroid gland is one of the most radiosensitive organs in the human body, with a particular vulnerability to stochastic effects such as radiation-induced malignancy. Thyroid collars, typically with 0.5 mm Pb equivalence, are worn in conjunction with aprons to protect this sensitive area, especially during prolonged or repeated exposure, as seen in fluoroscopically guided interventions. Regular use of thyroid protection is recommended by radiation safety organizations to mitigate long-term health risks to medical personnel. Leaded eyewear is increasingly recognized as essential PPE, especially for interventional radiologists and cardiologists. The eye lens is highly susceptible to radiation-induced cataracts, which were previously classified as a deterministic effect but are now understood to occur at lower dose thresholds. Leaded glasses with side shields and a lead equivalence of 0.5 to 0.75 mm can reduce lens exposure by up to 70–90%, depending on the design and fit. Custom-fitted eyewear or prescription-integrated designs are now widely available to enhance compliance and comfort. Leaded gloves are used in situations where the hands may enter the radiation field, such as during catheter placement or image-guided biopsy procedures. However, these gloves typically offer lower attenuation (0.25 mm Pb equivalent or less) due to the need for tactile feedback and manual dexterity. Moreover, their improper use within the primary beam can

paradoxically increase exposure due to automatic exposure control (AEC) compensation, and as such, their use is recommended primarily for scatter fields.

### 16.3. PROTECTIVE BARRIER

In the field of radiology and radiographic imaging, the use of protective barriers is fundamental to ensuring the safety of healthcare workers, patients, and the general public from the harmful effects of ionizing radiation. Ionizing radiation, while invaluable for diagnostic and therapeutic purposes, poses potential biological risks if not properly controlled. Protective barriers are physical structures or materials designed to absorb or attenuate radiation to levels that are within the recommended safety limits established by authoritative bodies such as the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and in India, the Atomic Energy Regulatory Board (AERB). The implementation of these barriers is governed by scientific principles of radiation physics, shielding calculations, and regulatory requirements. Protective barriers in radiology are broadly categorized into two types: primary protective barriers and secondary protective barriers.

#### 16.3.1. Primary Protective Barriers

Primary barriers are structural elements specifically designed to intercept the primary or useful X-ray beam—the direct radiation emitted from the X-ray tube toward the patient. These barriers constitute the first and most critical line of defense against high-intensity radiation in diagnostic and interventional radiology. Because they are directly exposed to the unattenuated beam, their design and composition are of paramount importance to ensure effective protection for both radiology personnel and individuals in adjacent areas. Primary barriers are strategically positioned in locations where the primary beam is routinely directed during clinical procedures. Common examples include the wall located directly behind a vertical Bucky stand, the floor beneath a fixed table-mounted X-ray system, or any surface consistently targeted during imaging. The materials selected for primary barriers must possess high atomic numbers ( $Z$ ) and high density, both of which contribute to superior radiation attenuation capabilities. The most commonly used materials are lead sheets and high-density concrete, though other shielding materials such as steel or barium-impregnated panels may be used in specific scenarios. The thickness of a primary barrier is meticulously calculated based on several critical parameters:

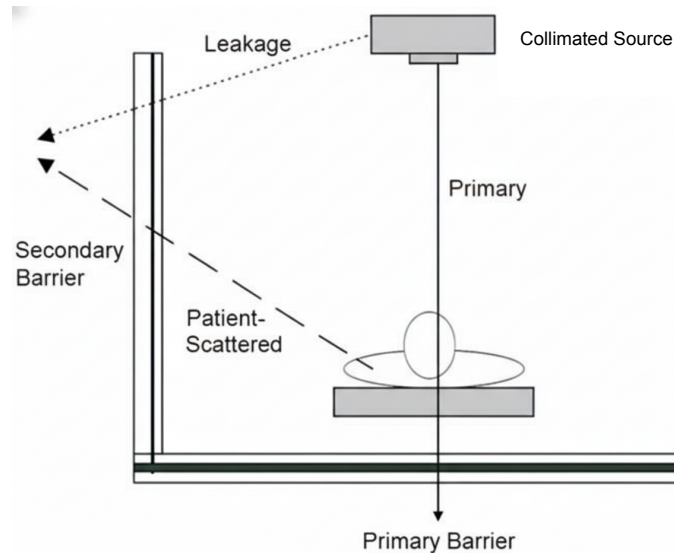
- Peak kilovoltage (kVp) of the X-ray beam, which influences the beam's penetrability
- Workload ( $W$ ), reflecting the volume and frequency of X-ray usage (measured in mA-min/week)
- Distance ( $d$ ) from the X-ray source to the barrier, based on the inverse square law
- Use factor ( $U$ ), indicating the proportion of time the primary beam is directed at the barrier

These variables are integrated into shielding equations to determine the appropriate material thickness required to attenuate the radiation to acceptable levels, as defined by national and international regulatory bodies. In the context of general diagnostic radiology, a lead equivalent thickness of 1.5 mm or more is commonly employed for primary barriers. However, in high-energy imaging environments such as computed tomography (CT) or fluoroscopy rooms, additional thickness or denser materials may be required. Properly constructed primary barriers are essential for maintaining radiation doses to occupational workers and the public within recommended limits, such as 20 mSv/year for radiation workers and 1 mSv/year for the general public, as per guidelines issued by the ICRP, NCRP, or local authorities like AERB. The effective implementation of primary barriers not only ensures regulatory compliance but also fosters a culture of radiation safety and best practices in radiologic imaging environments.

#### 16.3.2. Secondary Protective Barriers,

Secondary protective barriers are structural components specifically engineered to shield against scattered radiation and leakage radiation—two forms of indirect radiation that occur during the operation of diagnostic X-ray equipment. Unlike primary barriers, which are positioned to intercept the direct beam, secondary barriers are located in areas of the radiographic suite that are not directly exposed to the primary X-ray beam. Their role is critical in ensuring comprehensive radiation protection, particularly in spaces occupied by healthcare staff,

patients, and the general public during or after imaging procedures. Scattered radiation arises when the primary X-ray beam interacts with the patient or other objects in the room, resulting in a change of direction and a significant reduction in energy. Leakage radiation, on the other hand, emanates from the X-ray tube housing itself and escapes through its protective shielding. Although both types of radiation are of lower intensity compared to the primary beam, they still pose a potential hazard, particularly over time or in high-workload environments. Consequently, secondary barriers are installed in all surfaces not designated as primary barriers, including side walls, ceilings, floors, control booth walls, and any adjacent spaces that might be affected by scatter or leakage.



**Fig: 16.1. Primary and Secondary Barrier**

Because the intensity of radiation encountered by secondary barriers is significantly lower, the shielding requirements are correspondingly reduced. These barriers are typically constructed from lighter or thinner materials, which are still effective in attenuating lower-energy radiation. Common materials include lead sheets with reduced thickness, lead-lined gypsum boards, steel panels, or multiple layers of standard drywall (gypsum board). A typical lead equivalent thickness for secondary barriers is around 0.8 mm, though this value may vary based on detailed shielding calculations. The required thickness of secondary barriers is determined by factors such as:

- Workload (W) of the X-ray system
- Scatter angle and distance from the patient or radiation source
- Occupancy factor (T) of adjacent areas
- Radiation energy levels, typically defined by the peak kilovoltage (kVp)

These considerations ensure that radiation exposure remains within regulatory dose limits, particularly the recommended occupational limit of 20 mSv/year and the public exposure limit of 1 mSv/year, as specified by organizations such as the International Commission on Radiological Protection (ICRP), National Council on Radiation Protection and Measurements (NCRP), and local regulatory agencies like the Atomic Energy Regulatory Board (AERB) in India.

### 16.3.3. Control Booth/Control Panel

An integral component of secondary protective shielding is the control booth, which houses the radiologic technologist during exposures. The control booth is built using appropriate shielding materials to safeguard the operator from scatter and leakage radiation. It must be located such that the primary beam cannot be directed toward it under any circumstances. The booth typically includes a lead-glass observation window with at least 2 mm lead equivalent thickness, enabling the technologist to monitor the patient while remaining protected. The

walls of the control booth are similarly lined with lead or equivalent materials to a height of approximately two meters, ensuring adequate shielding for personnel who spend significant time in this location. In addition to fixed structural barriers, mobile Protective Barrier (MPB) and personal protective barriers are employed in radiology, particularly in settings where the construction of permanent shielding is impractical or during portable radiographic procedures. Mobile lead shields are freestanding, wheeled devices that incorporate lead panels and leaded glass viewing windows. They are commonly used in intensive care units, operating theaters, and emergency departments where portable X-ray units are deployed. These barriers allow for flexible yet effective protection for staff who must remain near the patient during imaging.

Personal protective equipment (PPE) forms another essential layer of radiation protection, especially in fluoroscopy, interventional radiology, and portable imaging. These include lead aprons, which typically offer 0.25 to 0.5 mm lead equivalent protection, as well as lead thyroid shields, lead gloves, and leaded eyewear. Such PPE is vital in reducing occupational exposure, particularly in procedures with prolonged exposure times or repeated imaging sequences. However, it is important to note that while PPE provides substantial protection, it is considered supplementary to structural shielding and should not replace proper room design. The design of radiology facilities and the implementation of protective barriers are guided by detailed shielding calculations, which consider various factors including the workload (typically measured in milliamperes-minutes per week), use factor (the percentage of time a beam is directed at a given barrier), occupancy factor (how often the space adjacent to the barrier is occupied), distance from the X-ray source, and the radiation quality (kVp). The objective is to ensure that radiation exposure levels in all occupied areas outside the imaging suite remain within recommended dose limits generally not exceeding 20 millisieverts (mSv) per year for occupational workers and 1 mSv per year for members of the general public.

**Table: 16.1. Difference between Shielding and Barrier**

Aspect	Shielding	Barrier
Definition	Technique or process to attenuate radiation	Physical structure that contains shielding
Function	Minimizes radiation exposure	Acts as a medium to implement shielding
Material Involvement	Involves selection and calculation of materials like lead or concrete	Made using shielding materials
Example	Use of 2 mm lead to block X-rays	A wall with 2 mm lead lining
Scope	Conceptual and design-based	Physical and structural

#### 16.4. FACTORS AFFECTING THE BARRIER THICKNESS

The design of protective barriers in radiology is a scientifically rigorous process that aims to ensure effective radiation shielding while maintaining functional and accessible imaging environments. Several critical factors must be taken into account during the planning and construction phase of any radiographic facility to meet safety standards and comply with national and international regulatory guidelines. These factors include the workload (W), use factor (U), occupancy factor (T), distance (d), radiation quality, and the intended shielding goals. Each of these parameters plays a pivotal role in determining the type, thickness, and placement of shielding materials required to attenuate radiation to safe levels for both occupational workers and the general public.

##### 16.4.1. The workload (W)

The workload (W) in radiographic shielding design denotes the total operational output of an X-ray machine over a specific period and is typically measured in milliamperes-minutes per week (mA-min/week). It serves as a quantitative measure of radiation usage, reflecting the frequency, duration of exposures, number of patients examined, and the nature of the radiographic procedures performed. A higher workload indicates more extensive and consistent use of the imaging equipment, necessitating more robust and comprehensive shielding solutions to ensure safety. For instance, a general diagnostic radiography room functioning five or more days a week with numerous daily imaging sessions will accumulate a significantly greater workload compared to a dental radiographic unit, which may operate infrequently with lower exposure levels. Accurate estimation of the

workload is critical, as it directly influences the calculation of required barrier thicknesses and the overall shielding strategy. Underestimating the workload could result in insufficient protection, while overestimating may lead to unnecessary construction costs. Therefore, workload assessments should be based on empirical data, clinical schedules, and equipment specifications to ensure both safety and cost-efficiency in shielding design. Workload calculation is a crucial aspect of designing radiation shielding in radiology departments. It quantifies the amount of radiation produced by imaging equipment over a specific time frame, usually per week, and is expressed in milliamperere-minutes per week (mA·min/week). This measurement helps determine the level of shielding required to protect healthcare workers and the public from radiation exposure. Workload is calculated by multiplying the tube current (in milliamperes), the duration of each exposure (in minutes), and the number of exposures performed in a week.

$$W = (\text{mA}) \times (\text{time per exposure in minutes}) \times (\text{number of exposures per week})$$

**For example**, if a general radiography room performs 100 chest X-rays per day using a tube current of 100 mA and an exposure time of 0.1 seconds (or 0.00167 minutes), the daily workload would be  $100 \text{ mA} \times 0.00167 \text{ minutes} \times 100 \text{ exposures} = 16.7 \text{ mA}\cdot\text{min}/\text{day}$ . Over a 5-day workweek, the total workload would be  $83.5 \text{ mA}\cdot\text{min}/\text{week}$ .

Different procedures vary in exposure time and mA settings, so for rooms handling a range of imaging tasks—such as fluoroscopy or CT—individual workloads for each type of exam are calculated and then summed. Additionally, published guidelines like those from the NCRP often provide standard workload values for various imaging modalities to assist in planning. Shielding design also takes into account other critical factors alongside workload, such as the use factor (how often a barrier is exposed to the primary beam), occupancy factor (how frequently adjacent areas are occupied), the distance from the radiation source, and permissible dose limits set by regulatory authorities. These elements work together to ensure that shielding is adequate and complies with safety standards. In general, conservative estimates are preferred during workload assessment to ensure maximum protection.

#### 16.4.2. The use factor (U)

The use factor (U) is a critical parameter in radiation shielding design that quantifies the fraction of time the primary X-ray beam is directed toward a specific barrier, such as a wall, floor, or ceiling. Expressed as a dimensionless fractional value between 0 and 1, it directly influences the determination of whether a surface should be treated as a primary or secondary barrier, and subsequently dictates the level of shielding required. The use factor is highly dependent on the room layout, equipment configuration, and clinical practices. For instance, in an X-ray suite with a fixed tube orientation where the beam is routinely aimed at a specific wall behind the examination table, that wall may have a use factor close to 1.0, indicating it is almost always exposed to the primary beam and therefore must be treated as a primary barrier. Conversely, a side wall or ceiling that rarely or never receives the primary beam may have a use factor of 0, qualifying it as a secondary barrier, which requires significantly less shielding. In a more dynamic setting, such as an interventional fluoroscopy room with a rotating C-arm or portable radiography unit, the use factor must be estimated based on typical clinical operations and the expected frequency with which the beam is directed at different surfaces. For example, if a particular wall receives the direct beam in approximately 25% of exposures, its use factor is 0.25. Accurately assigning use factors is essential for optimized shielding design. Overestimating the use factor can lead to excessive shielding costs, while underestimating it may result in inadequate radiation protection, potentially exposing personnel and the public to doses above recommended safety limits. Regulatory guidelines, such as those from the National Council on Radiation Protection and Measurements (NCRP) or the Atomic Energy Regulatory Board (AERB), often provide standardized use factors for various clinical scenarios. These guidelines serve as reference points during the planning and construction of radiology facilities to ensure that shielding is both effective and cost-efficient.

#### 16.4.3. Occupancy Factor

The occupancy factor (T) is a critical component in the design of radiation shielding, representing the fraction of

time that an adjacent or nearby space is occupied by individuals who could potentially be exposed to radiation. It is a dimensionless value ranging from 1 to as low as 1/20, and it plays a pivotal role in determining the thickness and extent of shielding required for walls, floors, and ceilings in diagnostic imaging facilities. This factor ensures that shielding design is proportional to the level of potential exposure based on how often people are present in surrounding areas. The principle is straightforward: the more frequently a space is occupied, the higher the risk of exposure, and hence, the greater the need for robust shielding to keep radiation doses within the regulatory limits 20 mSv/year for occupationally exposed workers and 1 mSv/year for the general public. To standardize design practices, occupancy factors are typically divided into three categories based on the nature and duration of space usage:

1. **Fully Occupied Areas (T = 1):** These are spaces that are continuously or routinely occupied by individuals for extended periods during the day. Examples include: Offices, Nursing stations, Examination rooms, Treatment rooms, Waiting areas, School classrooms. In these areas, people may remain for several hours, often throughout the workday. Because of this high occupancy, they are assigned the maximum occupancy factor of 1, which means shielding must be most comprehensive in these directions.
2. **Partially Occupied Areas (T = 1/2 to 1/5):** These areas are occupied intermittently or for shorter durations. While not continuously staffed, they are accessed frequently enough to warrant moderate shielding. Examples include: Corridors, Patient holding areas, Staff lounges, Toilets. A typical occupancy factor for such spaces is between 1/2 and 1/5, depending on the specific usage and time spent in the area.
3. **Occasionally Occupied or Low-Use Areas (T = 1/10 to 1/20):** These are areas that are rarely or sporadically used, often for maintenance or storage purposes. Examples include: Janitor's closets, Electrical or mechanical rooms, Stairwells, Storage rooms, Crawl spaces, Roof access areas. Due to infrequent occupation, these areas are assigned low occupancy factors, typically 1/10 or 1/20, allowing for reduced shielding requirements without compromising safety.

**Application in Shielding Design:** When incorporated into shielding calculations alongside other key parameters such as workload (W), use factor (U), distance (d) from the X-ray source, and radiation quality (kVp) the occupancy factor ensures that radiation protection measures are appropriately scaled to the risk level of each adjacent space. For instance, a wall shared with a fully occupied office will require substantially more shielding than one adjacent to a lightly used storage closet. Regulatory and advisory bodies such as the National Council on Radiation Protection and Measurements (NCRP), the International Commission on Radiological Protection (ICRP), and national authorities like the Atomic Energy Regulatory Board (AERB) in India provide guidelines for assigning occupancy factors during facility planning. By adhering to these recommendations, healthcare facilities can effectively balance radiation safety with economic feasibility, ensuring that all individuals, whether patients, staff, or the public, are protected from unnecessary radiation exposure.

#### 16.4.4. Other Factors

**Distance (d):** Distance refers to the straight-line measurement from the X-ray source to the point of interest on a protective barrier or to the location where radiation exposure needs to be minimized. It is a fundamental parameter in radiation protection, governed by the inverse square law, which states that the intensity of radiation is inversely proportional to the square of the distance from the source:

$$\text{Intensity} \propto \frac{1}{d^2}$$

This means that doubling the distance from a radiation source reduces the radiation intensity to one-quarter, significantly impacting the level of exposure and the design of shielding structures. In practical shielding design, increasing the distance between the X-ray tube and occupied areas can lead to a substantial reduction in required shielding thickness. For instance, walls or barriers that are farther from the source may only need minimal shielding compared to those in closer proximity. This principle is especially useful in the architectural planning of imaging facilities, where thoughtful room layout can reduce both radiation exposure and construction costs. Design strategies might include placing high-occupancy rooms (e.g., offices or control rooms) further from high-

exposure zones or using corridor buffers to increase physical separation. Regulatory guidelines often require shielding calculations to account for the minimum expected distance, ensuring protection even under the least favorable conditions. Therefore, accurate measurement and documentation of source-to-barrier distances are crucial during facility planning and construction.

**Radiation Quality (kVp):** Radiation quality refers to the energy characteristics of the X-ray beam, typically represented by the peak kilovoltage (kVp). It is a critical parameter in shielding design because it directly affects the penetrating ability of the radiation and the attenuation properties required of shielding materials.

Higher kVp values produce X-ray photons of greater energy and penetration, meaning they can pass through more material and pose a higher risk to adjacent areas. As such, procedures that involve high-energy beams, such as computed tomography (CT), fluoroscopy, and angiographic studies, necessitate thicker or denser shielding materials, such as high-density lead, steel, or concrete. For example, CT rooms often require 2 mm or more lead equivalent shielding, whereas standard diagnostic radiography rooms may only require 1.5 mm or less. Conversely, procedures that use lower kVp settings, such as dental radiography or extremity imaging, generate softer X-ray beams that are more easily attenuated, requiring comparatively less shielding. In these scenarios, thinner lead panels or even lead-equivalent drywall may suffice.

## 16.5. SHIELDING MATERIALS

In radiology, shielding materials are used to protect patients, healthcare workers, and the general public from the harmful effects of X-rays and other forms of ionizing radiation. The main goal of shielding is to reduce the amount of radiation that escapes from the X-ray room to surrounding areas. The choice of material depends on how strong the radiation is, how often the equipment is used, and where the radiation might travel. The most important qualities of a shielding material are its ability to absorb radiation and prevent it from passing through.

### 16.5.1. Lead (Pb)

Lead is one of the most widely used and effective materials for protecting against radiation in radiology. This is because it has a very high atomic number and density, which means it can absorb and stop X-rays very efficiently. Even a thin sheet of lead can significantly reduce radiation exposure, making it a reliable choice for shielding. Lead is used in many different forms depending on the application. It can be found as solid sheets, bricks, or flexible panels, and is commonly built into the walls, doors, and ceilings of X-ray rooms. Lead-lined walls and doors prevent radiation from escaping into adjacent areas where people might be present. It is also used in mobile shields that can be moved around the room as needed, and in control booths where radiographers operate the equipment. In addition to room protection, lead is a key material in personal protective gear. Radiology staff often wear lead aprons, thyroid collars, and lead gloves to protect themselves during procedures. The thickness of lead used depends on how intense the radiation is and how often the area or person is exposed. For example, walls directly in the path of the X-ray beam, known as primary barriers, may require 1.5 to 2 millimeters of lead. Areas exposed to scattered radiation or less frequent exposure might only need 0.5 to 1 millimeter of lead. Because of its effectiveness, lead continues to be a standard material in radiation protection. However, due to its weight and environmental concerns, researchers are also exploring lighter, lead-free alternatives for some applications.

### 16.5.2. Concrete

Concrete is widely utilized as a radiation shielding material, particularly in the construction of diagnostic radiology rooms, computed tomography (CT) suites, and radiotherapy treatment vaults. Although concrete is less dense than lead, it compensates for this by being applied in significantly greater thicknesses to achieve adequate attenuation of ionizing radiation. A key advantage of concrete lies in its cost-effectiveness, structural strength, and ease of incorporation into conventional building processes, allowing it to serve dual roles as both a shield and a structural element (e.g., walls, ceilings, and floors). For standard diagnostic X-ray facilities, typical concrete shielding requirements range from 30 to 40 centimeters in thickness, depending on the workload, usage patterns, and type of imaging performed. In environments utilizing higher energy radiation—such as CT scanners or linear

accelerators (LINACs)—the required shielding effectiveness may necessitate the use of high-density concrete. This specialized form of concrete is formulated using heavy aggregates like barite, magnetite, or hematite, which enhance its radiation attenuation capacity. High-density concrete is especially valuable in settings where spatial constraints prevent the use of thick conventional concrete barriers.

### **16.5.3. Lead-Lined Gypsum Board (Lead-Lined Drywall)**

Lead-lined gypsum board, also referred to as lead-lined drywall, is a specialized construction material widely employed for radiation shielding in diagnostic and therapeutic radiology facilities. It consists of a standard gypsum wallboard with a continuous sheet of lead laminated to one surface. This design enables effective radiation protection while allowing the use of conventional building techniques, facilitating integration into standard framing systems. These panels are primarily used for secondary radiation protection, meaning they are typically installed in areas exposed to scattered or leakage radiation rather than direct primary beams. Common applications include wall assemblies in X-ray rooms, CT suites, dental operatories, and nuclear medicine facilities. Lead-lined drywall is available in various thicknesses to suit specific shielding requirements, generally beginning at 1 mm lead equivalent. Thicker lead sheets may be used depending on the energy of the radiation and the design workload of the facility. The lead sheet is factory-bonded to the drywall to ensure structural integrity, and the boards are installed with overlapping seams and protective lead strips or batten strips to maintain shielding continuity. This type of shielding offers the advantage of ease of installation, cost-effectiveness, and adaptability to architectural needs, making it a common solution for enhancing radiation safety in medical environments.

### **16.5.4. Lead Glass (X-ray Protective Glass)**

Lead glass, also known as X-ray protective glass, is a specialized transparent shielding material that incorporates a high concentration of lead oxide and other heavy metal oxides into its composition. This unique formulation provides effective attenuation of ionizing radiation while maintaining optical clarity, making it ideal for environments where both visibility and radiation protection are essential. The primary application of lead glass is in viewing windows and observation panels, which are typically integrated into the walls or doors of diagnostic imaging rooms. It plays a crucial role in control rooms, allowing radiologic technologists to maintain direct visual contact with the patient during imaging procedures—such as X-ray, fluoroscopy, or computed tomography—without being exposed to harmful radiation. Lead glass is manufactured in various thicknesses, commonly offering radiation protection equivalent to 1.5 to 2 mm of solid lead. The level of shielding provided depends on the thickness and lead content of the glass, which can be selected based on the energy levels of the radiation in use. In addition to its radiation protection capabilities, lead glass is designed to be scratch-resistant and may also be laminated for enhanced durability and safety. It is an essential component of modern radiological facility design, ensuring both safety and operational efficiency.

### **16.5.5. Lead Free Shielding**

Lead-free shielding is an advanced and increasingly popular alternative to traditional lead-based materials used in radiation protection. While lead has historically been the standard for shielding against ionizing radiation due to its high atomic number and excellent attenuation properties, concerns about its toxicity and environmental hazards have prompted the development of safer alternatives. Lead is a known health hazard, especially with prolonged exposure, and its disposal poses significant environmental challenges. In response, lead-free shielding materials have been engineered to provide comparable radiation protection while eliminating the health and ecological risks associated with lead. Lead-free shielding materials are typically composed of a combination of heavy metals such as bismuth, tungsten, tin, antimony, and barium, which are embedded within a flexible polymer matrix. These elements possess high atomic numbers and densities, which allow them to absorb and attenuate X-rays and gamma rays effectively. The composite nature of these materials provides a balance between shielding efficiency and mechanical properties such as flexibility, durability, and weight. The use of polymer matrices not only enhances the flexibility and wearability of the shielding materials but also contributes to their chemical stability and resistance to wear and tear. These materials are manufactured in various forms to accommodate

different radiation protection requirements across medical and industrial settings. In clinical environments, lead-free shielding is commonly used in the production of personal protective equipment (PPE), such as aprons, thyroid collars, gloves, and gonadal shields. These garments are particularly beneficial in fluoroscopy, interventional radiology, and dental radiography, where healthcare personnel are frequently exposed to scattered radiation. Lead-free shielding is also utilized in structural applications, including wall panels, mobile barriers, observation windows, and protective drapes in operating rooms and catheterization labs. Additionally, transparent lead-free acrylic or composite glass is used in viewing panels, allowing for both visual observation and radiation safety.

One of the most significant advantages of lead-free shielding is its non-toxic nature, making it safe for routine handling and reducing occupational health risks. Unlike lead, these materials do not pose a threat of bioaccumulation or contamination during use or disposal. This characteristic is especially important in environments where protective garments are used regularly, such as pediatric radiology, where staff may wear protective aprons for extended periods. Furthermore, lead-free shields are generally lighter than their lead counterparts, thereby reducing physical strain and the risk of musculoskeletal disorders among healthcare workers. The lighter weight and improved ergonomics contribute to greater user compliance and comfort during long procedures. In terms of performance, lead-free shielding materials are carefully engineered to match the attenuation capabilities of traditional lead-based products. The shielding efficiency is typically expressed in terms of lead equivalence, such as 0.25 mm Pb, 0.35 mm Pb, or 0.5 mm Pb, based on standardized testing using diagnostic X-ray energy ranges (typically 70 to 150 kVp). High-quality lead-free composites can achieve similar or even superior attenuation when compared to lead of the same equivalence, depending on the specific composition and construction of the shielding material. However, to achieve the same level of protection, lead-free materials may sometimes require greater thickness, which can slightly offset the weight advantage in certain applications.

Despite their many benefits, there are a few limitations associated with lead-free shielding. The cost of manufacturing these advanced materials tends to be higher than traditional lead, which can impact budgeting in some facilities. Additionally, while lead-free materials are generally more flexible and durable, certain polymer-based composites may be more susceptible to degradation over time, especially if exposed to harsh disinfectants or mechanical stress. Nevertheless, continuous improvements in material science and manufacturing processes are addressing these challenges, making lead-free shielding increasingly robust and cost-effective. Environmental sustainability is another key factor driving the adoption of lead-free shielding. These materials are compliant with international environmental and safety regulations such as the Restriction of Hazardous Substances (RoHS) Directive and are easier to recycle or dispose of compared to toxic lead-based waste. This makes them an ideal choice for institutions committed to green healthcare practices and sustainable facility management. By reducing hazardous waste and minimizing the environmental footprint of radiology departments, lead-free shielding contributes to broader public health and ecological goals.

## **16.6. AERB GUIDELINES FOR SHIELDING IN DIAGNOSTIC RADIOLOGY FACILITIES**

The Atomic Energy Regulatory Board (AERB) of India, as the statutory authority responsible for radiation safety, has issued detailed guidelines for the design and implementation of shielding in diagnostic radiology facilities. These guidelines ensure that ionizing radiation exposure to patients, healthcare personnel, and the public remains within internationally accepted safety limits. The shielding requirements vary depending on the location within the facility specifically the X-ray room itself, the control room, and adjoining areas such as waiting rooms or corridors and are carefully prescribed based on the type of radiation, intensity, occupancy, and usage patterns.

### **16.6.1. Shielding of the X-ray Room**

The X-ray room is the primary source of ionizing radiation during diagnostic procedures, and thus demands the most stringent shielding measures. The AERB mandates that the walls, ceiling, and floor enclosing the X-ray room must be designed as primary barriers capable of attenuating the direct X-ray beam to a level that reduces radiation exposure outside the room below permissible limits. Typically, this involves constructing barriers with

either high-density concrete or lead-equivalent materials. For diagnostic X-rays operating at peak voltages up to 150 kVp, the recommended thickness is approximately 30 to 40 cm of standard concrete or 1.5 to 2.0 mm lead equivalence. These thickness values are calculated considering the maximum workload, which represents the total exposure the equipment delivers weekly, the use factor indicating the fraction of the workload directed at each barrier, the occupancy factor reflecting the usage frequency of adjacent areas, and the distance from the source to the protected location. The design must also address potential weak points in the shielding, such as doors, windows, and ventilation ducts. AERB requires that doors to the X-ray room be lead-lined, with a lead thickness equivalent to or greater than that of the adjacent walls to maintain consistent attenuation. Viewing windows incorporated into the room must be made of lead glass or equivalent lead-free radiation-protective glass, typically providing protection equal to 1.5 to 2 mm of lead. Air vents must be designed to minimize radiation leakage, often employing labyrinthine or baffle structures filled with shielding materials. This comprehensive approach ensures that radiation does not escape through any gaps or unintended paths.

### 16.6.2. Shielding of the Control Room

The control room is typically located adjacent to or behind the X-ray room and is occupied by technologists or operators during imaging procedures. Unlike the X-ray room, the control room does not face the primary X-ray beam directly but is exposed to secondary radiation, including scattered radiation from the patient and leakage radiation from the X-ray tube housing. Consequently, the AERB prescribes the use of secondary barriers with somewhat reduced shielding thickness compared to primary barriers. The shielding requirements for control room walls are generally in the range of 1.0 to 1.5 mm lead equivalence, designed to attenuate scattered radiation to levels below the occupational dose limit, which for radiation workers is typically set at 20 mSv per year (or an equivalent weekly limit). The occupancy factor for control rooms is taken as 1 (full occupancy), reflecting continuous staff presence during working hours. The control room must also have a lead glass window allowing the operator visual access to the patient during imaging while maintaining radiation safety. The lead glass usually provides protection equivalent to 1.5–2.0 mm of lead. Additionally, the control room's shielding design must consider factors such as the X-ray tube orientation and the distance between the source and the control room to optimize protection. Proper layout planning is essential to ensure that the operator is not exposed to unnecessary radiation.

### 16.6.3. Shielding of the Waiting Area and Other Uncontrolled Areas

Waiting areas, corridors, and other spaces adjacent to X-ray rooms are typically classified as uncontrolled areas, where the general public or non-radiation personnel may be present. The AERB sets much stricter dose limits for such areas, typically limiting radiation exposure to 1 mSv per year, which translates to approximately 20  $\mu$ Sv per week. Since these areas primarily receive scattered radiation that is significantly weaker than the primary beam, the shielding requirements are less stringent but still critically important. The barriers protecting these spaces are secondary barriers and generally consist of lead-lined drywall, lead-free composite panels, or concrete walls with thicknesses less than those used for primary barriers. The precise thickness depends on the workload, use factor (usually lower for scattered radiation), occupancy factor (which varies depending on whether the space is fully or partially occupied), and distance from the source. For example, if a waiting room is adjacent to an X-ray room wall that receives only scattered radiation, a lead-equivalent thickness of around 0.25 to 0.5 mm may suffice, or concrete of reduced thickness relative to primary barriers. The shielding calculations account for the fact that waiting areas may be occupied continuously, so even low levels of scattered radiation must be adequately controlled.

End of Chapter

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