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Radiation Transmission-based Thickness Measurement Systems - Theory and Applications to Flat Rolled Strip Products

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1. Introduction

Precise, accurate measurement of strip / sheet thickness is critical in the controlled processing and quality assessment of flat rolled metal products. Through the years, many methods (both contact and non-contact) have been developed, each having specific, relevant applications, and certain characterizable advantages and disadvantages. These systems are provided in a variety of geometries and physical arrangements, and seemingly endless collections of functions and features.

One particular non-contact method employs an understanding of a material's reaction to incident radiation (primarily the photonic / gamma form – although electron / beta radiation can also be considered) in a transmission mode framework. Here, semi-collimated, high energy radiation (a photon beam of a given spectral content) is directed perpendicular to one surface of the flat strip material. Depending on the energy level, the incident radiation interacts with the material's atomic structures and is either passed, absorbed, scattered or involved in high energy pair productions. The resulting transmitted radiation appears as a dispersed beam pattern, having attenuated intensity and modified spectral content. A portion of the exiting radiation is collected by detection instruments which render a signal functionally related to the integral of the received radiation intensity over the detector's spectral bandwidth. Knowledge of the radiation source's intensity and spectral content, the material chemistry and the detector's response characteristics are needed to process the signals and render a thickness measurement.

Typically, the plane of the strip is oriented horizontally with the source and detector mounted above and below the stip. There are a number of different configurations ranging from stationary / physically-fixed source and detector arrangements above and below the strip, to C-Frame / O-Frame mounted configurations that (in some cases) allow for transverse strip thickness profiling, to multi-source / multi-detector arrangements that provide instantaneous measures of the strip profile. Regardless of the physical configuration, the fundamental physics applies.

This chapter is the first of a two-part discussion concerning the nature of radiation transmission-based strip thickness measurement. The intent of this chapter is to examine the underlying physics and methods of this approach, and functions as a tutorial supporting subsequent discussions (Zipf, 2010). Natural and artificial radiation sources are presented and discussed, along with the various means of containing and directing the emitted radiation. The nature of the material's interaction with radiation is analyzed and considered in the presence of possibly complex material chemistries. Detection system sensors and instrumentation are studied and examined with respect to their associated signal processing components and methods of rendering a thickness measurement. Calibration and standardization methods are introduced and combined with the various methods of resolving the material thickness from active measurements. Special functions and features (e.g., transverse profiling, strip quality control, etc.) are discussed and assessed. Classical system architectures and component organizations are presented and considered with respect to typical applications and system implementations.

2. Fundamentals of Non-Contact Radiation Attenuation Gauging

Radiation attenuation gauging involves the measurement of the thickness of a flat sheet of known (or calibrated) material composition, through the assessment of the degree of transmitted attenuation experienced by a beam of high energy ionizing radiation directed perpendicular to the planar surface of the material (I2S, 1992). Figure 2.1 provides a simplified diagram showing the primary concepts and components associated with this approach.

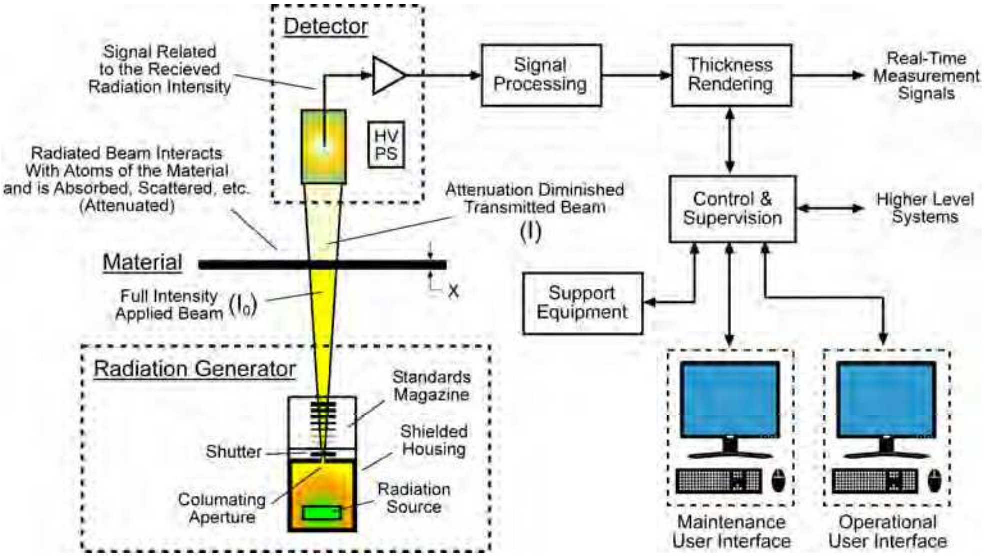


Fig. 2.1 – Diagram illustrating the primary concepts and components associated with transmission-based radiation attenuation gauging.

2.1 General System Objectives and Requirements

Objectives

- Provide a sufficiently accurate, precise, instrumented signal, representative of the measured strip thickness (with accuracy and repeatability < 0.1% of nominal).

Requirements

- Must be "continuous" in nature (not a spot measurement)
- Must measure over a reasonably small surface area (~25mm diameter circle)
- Must provide measurements while the strip is moving (at speed up to 1500 mpm)
- Must be fast responding (5-20msec)
- Must be independent-of or compensate-for alloy variances
- Must compensate for changes in ambient conditions
- Must be highly immune to noise and external interference
- Must not damage the strip surface
- Must provide flexible, multi-facetted interfacing to other systems
- Must provide intuitive, interactive user interfaces (both operational & maintenance)

Desirable Traits

- Measurement of the transverse strip profile
- Insensitive to strip shape / flatness, pass-line height, debris, oil & coolant films, etc.
- Employ Commercial-Off-The-Shelf (COTS) Technologies
- Safe for operational & maintenance personnel
- Physically / mechanically robust
- Real-Time, Interactive, Graphical User Interfaces (GUIs)
- Adaptable, scalable system arrangements & platforms
- Remote Accessibility

2.2 Primary Components

Radiation Generator – This device emits a directed beam of high energy ionizing radiation (of known intensity, I_0 (in photons/sec), and spectral characteristics) and provides radiation containment.

Shielded Housing – This vessel typically consists of a shielded, structural housing containing the associated holders and mounts required to locate and orient the radiation source. The housing may contain dielectric oil immersed components and be supported by an external heat exchanging / cooling system.

Radiation Source – This component generates the radiation that will be applied for measurement. The source may be either natural (radioactive isotope) or artificial (X-Ray tube), and may project a radiation pattern that is sensitive to alignment with the housing aperture.

Collimating Aperture – Radiation is emitted from the housing chamber through a sealed aperture in the form of a beam having a specific, semi-collimated optical geometry needed to support the form and geometry of the application and detector. The aperture is sealed to reduce the infusion of external contaminants and / or the escape of any (possibly pressurized) internally contained dielectric oil.

Shutter - This device provides a means of cutting off the radiation beam, making the radiation generator safe for handling and operations in the proximity.

Standards Magazine - This device contains a group of precision (often NIST traceable) samples that can be introduced into the radiation beam (individually or in groups) to provide a means of measuring the emitted beam's intensity and spectral content for calibration and standardization purposes. (Howard, 1970)

Material Under Measurement – For the purposes of this discussion, we will be considering flat rolled, sheet / strip products, composed of various metals (e.g., steel, aluminum, and copper / brass alloys, etc.) whose width is much larger than the nominal thickness. The strip may be stationary or moving at speeds exceeding 1500 meters/minute.

Detection System – Transmitted / scattered radiation, I (in photons/sec), that results from the incident radiation, I_0, penetrating the strip, is collected and measured by this device, which is typically located above the strip and aligned to the optical axis of the radiated beam. The radiation generator's collimator and detector aperture are sized to provide the detector an optical over-containment of the transmitted beam.

Detector – Collected incident radiation is converted to an electrical signal that is functionally related to the radiation intensity. Ion chambers and scintillation crystal / photomultipliers are often employed (Moore & Coplan, 1983).

High Voltage Power Supply – Detector sensitivity (gain) is related to the applied potential. A high voltage power supply provides the detector potential with sufficient current capacity to provide the necessary charge recovery.

Preamplifier – The feeble detector signal is amplified to usable amplitudes by a high gain, low noise electrometer / transconductance amplifier (Motchenbacher & Fitchen, 1973). To reduce signal noise and interference, it is desirable to place the preamplifier as close as possible to the detector and mounted in a shielded, hermetically sealed enclosure.

Signal Processing – The amplified detector signal requires wide bandwidth signal processing (in both time and amplitude) to render a calibrated measurement of the intensity of the received radiation (i.e., related to material absorption / attenuation). This processing can be provided by discrete electronics and instrumentation, real-time digital signal processors or Field Programmable Gate Arrays (FPGAs).

Thickness Rendering – This subsystem provides the final determination and distribution of the calibrated measurement of strip thickness. Calibration and alloy compensation curves reside in and are supplied by the System Supervisor. The measured thickness is typically transmitted via analog signals or high speed networked numerical data exchanges.

System Supervisor – This subsystem oversees and coordinates the gauging system's control, measurement, calibration and operational activities, along with any operational interfacing to the mill / line control systems.

User and Maintenance Interfaces – Depending on the nature and extent of the system's function, various forms of dedicated operator interfaces may be employed. The user interface can range from simple operator controls and data entry devices, to sophisticated interactive, graphical human machine interfaces (HMIs). The maintenance interface is typically more sophisticated and provides detailed graphical information concerning the status, activity, calibration and performance data, along with trouble shooting and diagnostic assistance.

Interfaces to External Control and Automation Systems – The gauging system must communicate and interact with the mill / line's related control, automation and high level production systems. Measured thickness indications are often transmitted as analog signals or numerically via dedicated network links. Set-up, operational and status data (i.e., nominal gauge sets, alloy / composition, profile / positioning, shutter, etc) are often exchanged via standard network, serial, or even discrete logic (BCD) interconnects.

3. Ionizing Radiation and Radiation Generators

Radiation is a generalized term used to describe a variety of energy forms that are emitted from a body. For the purposes of this discussion, we will focus on ionizing radiation which involves charged particles or electromagnetic waves possessing sufficient energy to dislodge strongly held electrons from atoms or molecules.

3.1 Forms of Radiation

Ionizing radiation comes in three(3) primary forms: (Halliday, 1955), (Kaplan, 1955)

α-Rays – Alpha radiation involves accelerated helium nuclei, composed of 2 protons and 2 neutrons. This particle has a high mass and a double positive charge. Due to its high mass, this form of radiation has low penetrating energy and a limited range. The primary source of formation is during the nuclear transformation process (radioactive decay), where a new element results.

β-Rays – Beta radiation involves accelerated electrons (or positrons). These particles have a low mass and a negative charge (positive for positrons). Beta rays have modest penetrating energy (more than alpha particles), but can be stopped by metals a few centimeters thick. The primary source of formation is during the nuclear transformation process (radioactive decay), where a neutron is converted to a proton (which remains in the nucleus) and an electron and an antineutrino are emitted. Beta radiation can also be formed by an electron gun in the presence of high electric field potentials.

γ-Rays – Gamma rays are high energy photon emissions (electromagnetic waves) (Kraus & Carver, 1973). Gamma radiation has high penetrating energy and is the primary form of radiation employed in strip thickness gauging systems. X-Rays are also a form of electromagnetic (gamma) radiation. Classically, Gamma Rays and X-Rays have been separated by their respective energy levels (with Gamma being of higher energy). However, a more common place distinction involves the means of their generation. We will examine the various aspects of these differences in the next section.

In fact, there are many forms of radiation (when considering the non-ionizing form), which include: neutron or proton emissions, acoustic, low energy electromagnetic radiation (i.e., thermal, black body, light, radio waves), etc. These forms of radiation are not considered within the scope of this discussion.

3.2 Radiation Sources

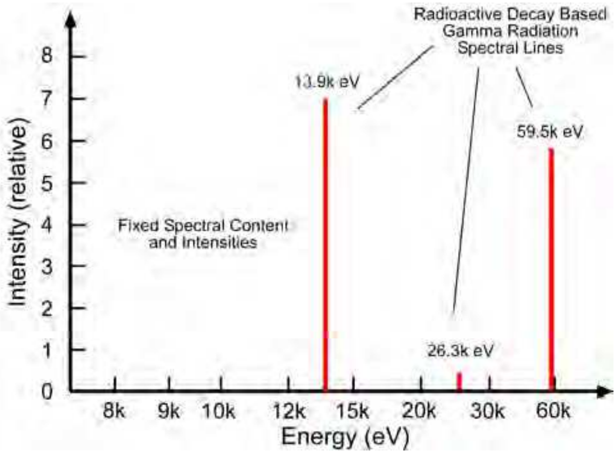
Radiation sources are components that generate radiation for application to the measurement process. To limit and direct this discussion, we will focus only on sources that produce high energy photons (electromagnetic waves or γ-Rays). Although β-Ray sources are common, a vast majority of the industrial applications employ γ-Ray emissions. As noted previously, it is necessary to draw specific distinctions between the forms of electromagnetic radiation, under consideration, in terms of their origins.

3.2.1 Naturally Occurring Gamma Rays (Isotope Sources)

Naturally occurring gamma rays are specifically produced by radioactive isotopes during the nuclear transformation process, where following the emission of alpha and / or beta radiation, the decaying nucleus releases excess energy (in the form of photons) to obtain an equilibrium (Halliday, 1955), (Kaplan, 1955). These photon emissions form very well defined spectral lines at specific energy levels and relative amplitudes (Halliday, 1955), (Graydon, 1950). Common radioactive isotopes are: Americium 241, Cesium 137, Curium 244. Figure 3.1 shows the spectral characteristics of photonic radiation released by the radioactive isotope Americium 241.

Primary Radiation			
Type	Energy	Unit	Relative Intensity
Alpha	5443	(keV)	84.5
	5485	(keV)	13
Beta	52	(keV)	< 1
Gamma	13.9	(keV)	42
	26.3	(keV)	2.4
	59.5	(keV)	35.9

(a)



(b)

Fig. 3.1 – Spectral characteristics of the radioactive isotope Americium 241: a) Table defining the form of radiation emitted, the energy level and relative intensity, b) Spectral characteristics of the Gamma radiation components.

3.2.2 Artificially Produced Gamma Rays (X-Ray Sources)

X-Rays (in this context) are specifically generated by high energy, inbound electrons interacting with the inner shell electrons of an atom or the atom's electric fields. These interaction processes, shown in Figure 3.2, produce two distinctly different spectral emissions.

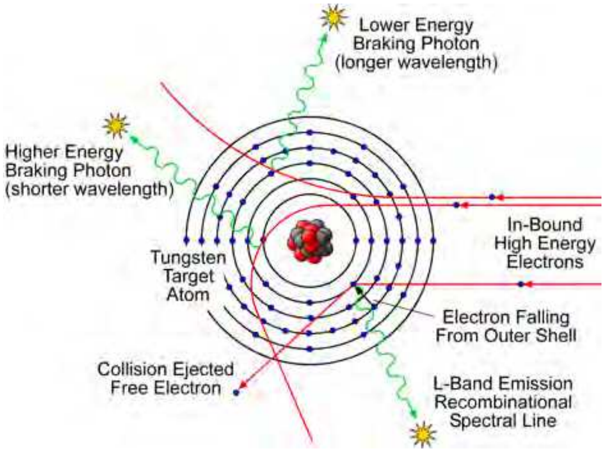


Fig. 3.2 – Nature of X-Ray generation via high energy electron interaction with a Tungsten atom based on a Bohr atomic model of the inbound electron interaction.

Characteristic Spectral Lines – Here an inbound high energy electron has sufficient energy to dislodge an atom's inner shell electron, to the extent of either lifting it to an outer shell (excited state) or removing it from the atomic union (ionized state). The shell's vacated electron position is filled (almost immediately), by a loosely bound electrons from the outer shells, resulting in a release of energy (in the form of a high energy photon), corresponding to the binding energies of the shells involved. The energy released produces discrete, well defined recombinational spectral lines (Mark & Dunn, 1985). The general characteristics of these spectral lines are shown in Figure 3.3 for Tungsten.

Bremsstrahlung Spectra – This spectral content develops when high kinetic energy electrons encounter the electric fields of the atom and are either decelerated or deflected from their previous trajectories (Halliday, 1955). The kinetic energy lost during this deceleration / deflection is emitted as electromagnetic radiation. An electron's inbound kinetic energy can be dissipated as X-Rays either entirely (in a single-stage nucleus encounter) or by several multi-stage encounters, each causing a different radiated energy. When an electron passes-by / interacts-with an atom, the proximity of its trajectory to the nucleus plays a direct role in the amount of energy dissipated. The probability of radiated energy dissipation elevates as the distance from the nucleus increases (i.e., larger distances from the nucleus induce weaker / more frequent radiation events, while shorter distances from the nucleus cause stronger / less frequent radiation events). The spectral content (shown in Figure 3.3) of the Bremsstrahlung component is not a discrete line spectra, but a continuum spanning the initial kinetic energy of the inbound electron (i.e., the maximum spectral energy equals the original kinetic energy of the electron) (Mark & Dunn, 1985).

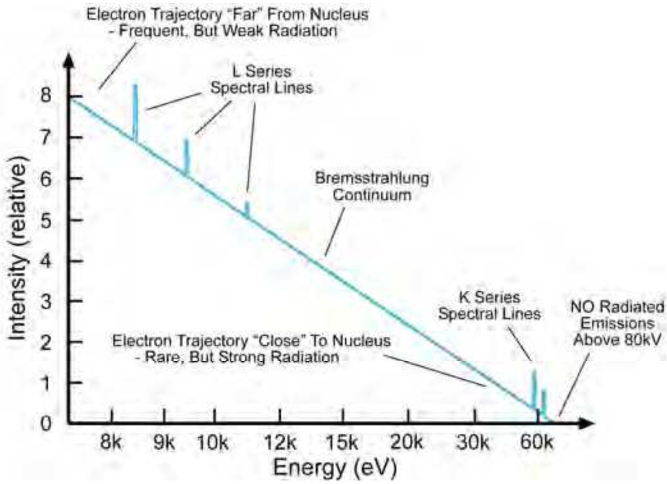


Fig. 3.3 – Spectral characteristics of an 80kV electron beam bombarding and interacting with the atoms of a Tungsten target.

3.3 Radiation Generation

The Radiation Generator emits a directed, collimated beam of high energy ionizing radiation and provides protective radiation containment. When considering isotope source based radiation generators, these devices are very simple (I2S, 1992). They contain only a shielded housing, an isotope source cartridge / pellet, source holder, columating aperture and a shutter. Due to the rather simplistic nature of these generators, we will forgo discussing their associated details.

3.3.1 X-Ray Generators

X-Ray source based radiation generators are far more complex than their isotopic counterparts. In the most classical sense, X-Ray generators are based on the components shown in Figure 3.4 and discussed in the following:

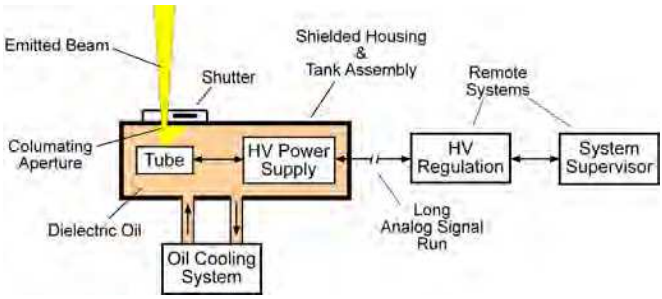


Fig. 3.4 – Block diagram illustration of the basic components associated with an X-Ray Generator.

X-Ray Tube – An X-Ray tube is a vacuum tube that when energized emits a polychromatic gamma ray spectrum (Howard, 1970), (Moore & Coplan, 1983). The spectral range is a direct function of the applied tube potential, and the intensity of the radiation is a direct function of the applied tube current. Figure 3.5 provide a diagram showing the primary components of an X-Ray tube.

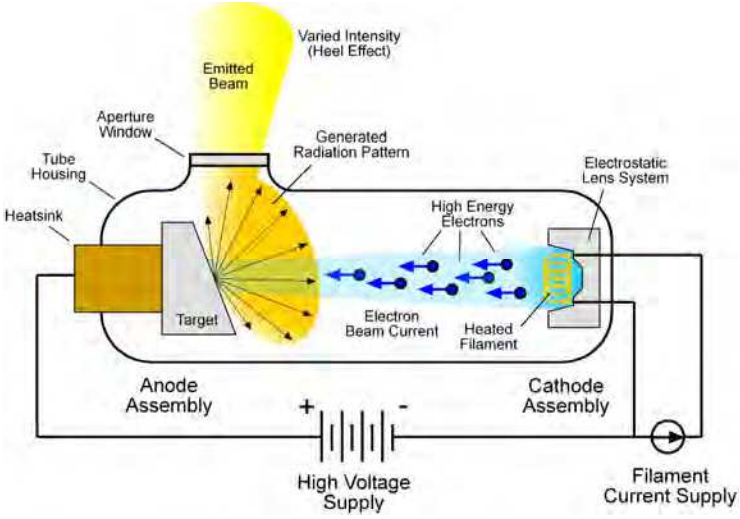


Fig. 3.5 – Simplified diagram showing the basic components of an X-Ray Tube.

Tube Housing – The tube is typically constructed of a sealed, cylindrical glass or ceramic housing and maintains a vacuum. Depending on the aperture material / mounting arrangement and the anode heat sink configuration, the tube geometry may have extensions or added structures, and can be shrouded by a circulating fluid heat exchanger cooling jacket.

Filament – This (typically) Tungsten coil is heated by a constant current source to temperatures that cause sufficient thermal excitation of the valence shell electrons to escape their atomic bonds and form a "cloud" of free electrons.

Target – This (typically) Tungsten plate emits polychromatic X-Rays when its atoms are bombarded by a beam of high kinetic energy electrons. The target's active surface is typically angled to direct the radiation pattern toward the tube's aperture. The angle must be optimized to provide the desired radiation intensity while still maintaining a concentrating projection of the applied electron beam pattern.

High Voltage Power Supply and Tube Potential – A high voltage, direct current (DC) power supply (often 10kV to 200kV) applies a precision regulated, potential between the filament (cathode) and the target (anode), to draw free, thermally excited electrons from the filament and accelerate them to their target impact energy, forming an electron beam. The beam's charge displacement forms a current across the tube (beam current). The power supply's current limits regulate the applied current / tube power. The high voltage electronics /

equipment is often immersed in a dielectric oil bath to provide insulation and allow for a more compact design. The high voltage power supply control and regulation are often provided by external equipment, possibly remotely located.

Electrostatic Lens – The geometric arrangement of this component forms electric field patterns that focus the electron beam to a specific target impact spot geometry (Harting & Read, 1976). Figure 3.6 provides an illustration of the formed electric field lines, and their impact on the electron trajectory.

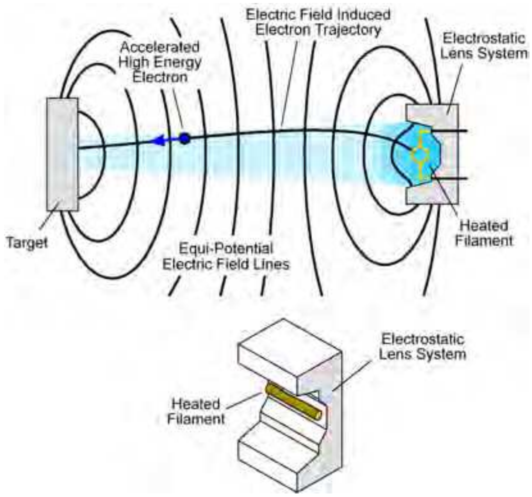


Fig. 3.6 – Block diagram illustration of the X-Ray Tube Electrostatic lens induced electric field lines and associated electron trajectory.

Dielectric Oil – The X-Ray tube and the high voltage power components are often immersed in an oil bath to provide both a high degree of electrical insulation and also a tube heat dissipation capacity.

Thermal Considerations – X-Ray tubes are highly inefficient, with only about 1% of the applied power being converted to X-Ray production. The remainder is converted to heat. Industrial X-Ray tubes are often immersed in an oil bath to dissipate the tube's thermal power. Depending on the tube power and the nature of the generator's housing, the generated heat may exceed the passive dissipation capabilities, thereby requiring an external, oil circulating, cooling / heat exchanging system.

Radiation Pattern and Heel Effect – The target's emitted radiation pattern is dependent on the angular orientation of the target and the spot-size / geometry of the electron beam. Figure 3.7 provides insight into the nature of these radiation patterns and heel effects. The lobed radiation pattern is caused by the angle at which the photons emerge from beneath the surface of the target at the focal point. This causes a differential attenuation of the photons that will ultimately compose a useful, emitted beam. The resulting radiation pattern emitted through the tube's aperture has radial / transverse variations in intensity (often termed "heel effect"), (Mark & Dunn, 1985).

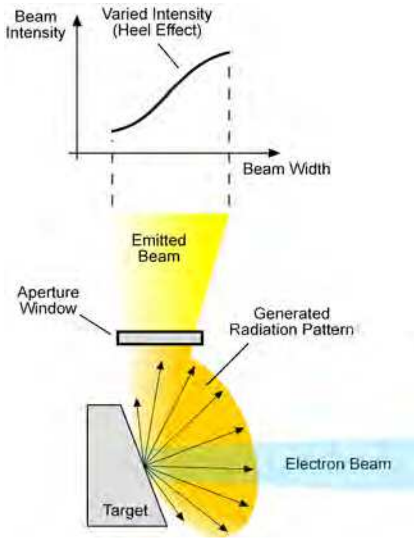


Fig. 3.7 – Illustration showing the varied intensity of the emitted beam associated with the geometry of the target, radiation pattern and location of the tube aperture window.

Tube / Tank Assembly – This component of the generator housing provides a sealed vessel in which the dielectric oil bath is contained and the tube / high voltage power components are mounted. This assembly typically utilizes a lead intermediate liner for radiation shielding and often employs an insulating inner liner (e.g., polypropylene).

Collimating Aperture – The geometry and location of this aperture (with respect to the X-Ray tube mounting and radiation pattern) defines the optical geometry and uniformity of the X-Ray generator's emitted beam. The aperture material will impact the radiated spectrum through energy dependent absorption and scattering processes. Depending on the nature of the tube / tank assembly and shielded housing, the aperture may be required to provide a fluid pressure seal to prevent dielectric oil seepage.

Shutter – A retractable shutter (typically lead) provides the ability to suppress the X-Ray generator's emission, while still allowing the X-Ray tube to be energized (often the tube is kept active to maintain a thermal equilibrium).

System Supervisor – This system component provides the desired references for the tube potential, beam current and filament current, and monitors the tube / tank status, temperature, etc. to control and oversee the generator's operations and performance.

Spectral Characteristics of the Tube / Generator Emitted Radiation – Within the X-Ray tube housing, the polychromatic spectral content of the produced radiation is based on the target material's characteristic and Bremsstrahlung spectra (see Figure 3.3). Beyond the tube's aperture and the aperture of the generator's collimator, the spectral content is modified by the absorption and scattering behavior of the aperture materials (possibly fused silica, calcium fluoride, beryllium, polypropylene, etc.) and any intervening dielectric oil. This causes an attenuation of the lower energy regions of the emitted spectrum (see Section 4.2

concerning the energy dependencies of the Mass Attenuation Coefficient). The resulting spectrum contains a higher energy content, making the beam more penetrating (harder). Figure 3.8 provides example plots of spectral content of Tungsten target radiation attenuated by a glass window aperture for differing applied tube potentials.

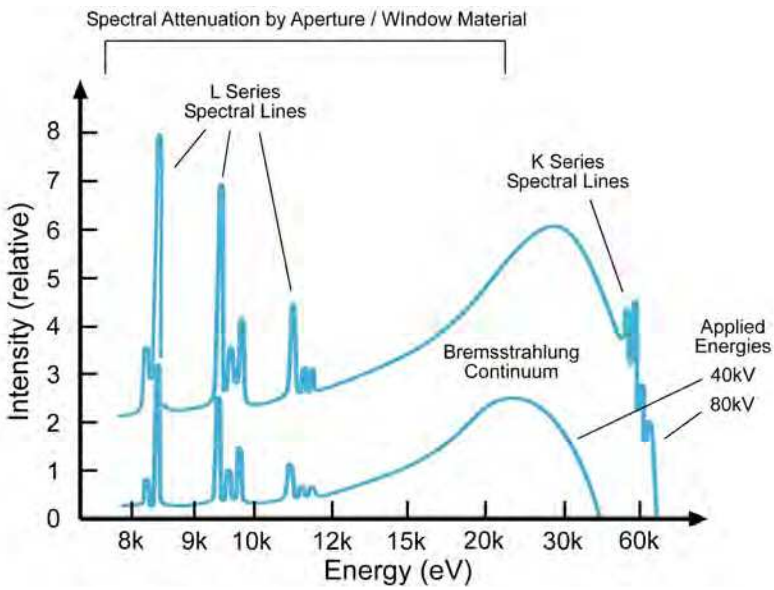


Fig. 3.8 – Graphical representations of the spectral content of the radiation emitted from a Tungsten target X-Ray tube with a glass aperture window, showing the Characteristic and Bremsstrahlung radiation spectrum for 80kV and 40kV tube potentials.

The key feature of this spectrum is the significant attenuation by the aperture window of the lower energy region (as noted by the diminished region of Bremsstrahlung radiation below 20kV). It is important to note that the lower tube potential (40kV) does not provide an electron beam with sufficient kinetic energy to dislodge the target material's K shell electrons (indicated by the lack of K Series recombinational spectral lines).

Controlled Variability of Tube / Generator Emissions – By varying the applied tube potential and beam current, the radiated tube / generator spectral content and intensity can be adjusted to meet the needs of the measurement application. Figures 3.9 and 3.10 show the reactions of the Bremsstrahlung radiation spectra to changes in the tube potential and beam current, respectively.

Beam Hardening – This term traditionally describes the process of increasing the average energy of the emitted spectrum. This causes the resulting beam to have a greater penetrating capability. Beam hardening can be achieved through the used of selected pre-absorbers, whose spectral attenuation characteristics suppress lower energy regions (compare Figures 3.3 and 3.8). This beam hardening effect can also be formed by increasing the applied tube potential. As shown in Figure 3.9, increasing the tube voltage causes the emitted spectrum's peak intensity to shift to higher energies.

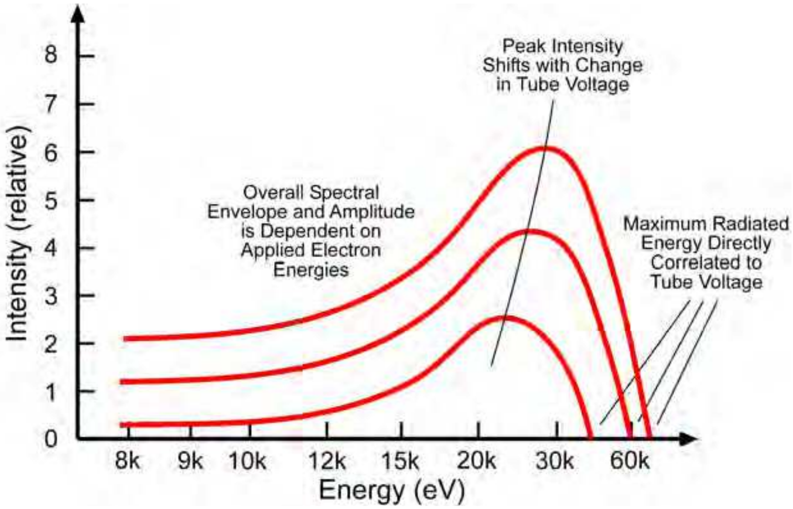


Fig. 3.9 –Illustration of the Bremsstrahlung spectra behavior due to variations in the applied tube potential, while maintaining a constant beam current. This illustrates that an increase in the tube voltage causes a beam hardening effect, by shifting the spectrum's average energy to higher (more penetrating) levels.

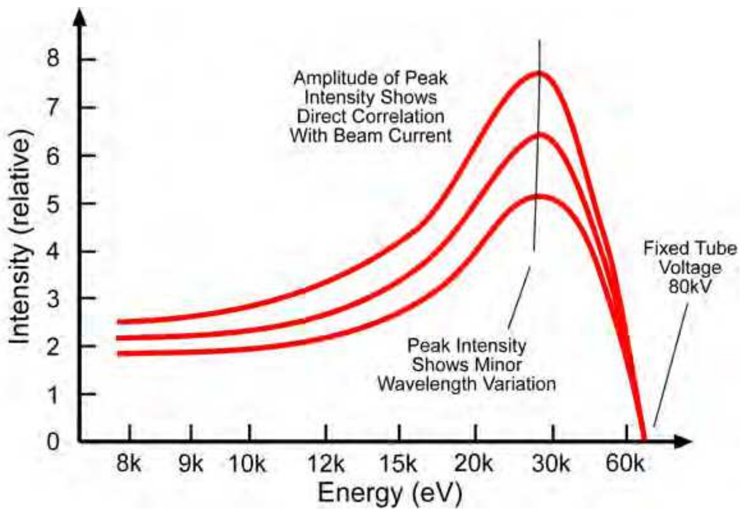


Fig. 3.10 –Illustration of the Bremsstrahlung spectra behavior due to variations in the applied beam current, while maintaining a constant tube potential.

4. Interaction of Radiation with Materials

The collimated beam of radiation emitted by the radiation generator is directed (typically perpendicular) to one surface of the material. The incident radiation interacts with the material's atomic structures and is either passed, absorbed, scattered or involved in high energy pair productions. The nature of this interaction is dependent on the spectral energy content of the applied radiation and the composition of the material. The resulting transmitted radiation appears as a dispersed beam pattern, having attenuated intensity and modified spectral content.

4.1 Attenuation Effects Based on Form of Radiation

The nature of the material interaction is dependent on the form and energy content (wavelength) of the inbound radiation. A number of processes are involved (e.g., collision, photoelectric absorption, scattering, pair production) and their cumulative effect can be characterized as an energy dependent attenuation of the intensity, and a modification of the radiated pattern of the transmitted beam (through scattering processes) (Kaplan, 1955), (Letokhav, 1987).

α-Particles – Due to their dual positive charge and their relatively large mass, Alpha particles interact strongly (through collision processes) with the material's atoms and are easily stopped (Kaplan, 1955).

β-Particles – Due to their physical mass and negative charge, Beta particles also interact through collision / scattering processes. Elastic and inelastic scattering processes are associated with manner in which inbound, high energy electrons interact with the electric fields of the material's atoms (Kaplan, 1955), (Mark & Dunn, 1985).

Inelastic Scattering – A certain amount of the inbound radiation energy is dissipated through an ionization or excitation of the material atoms. Here, the inbound energy is sufficient to dislodge electrons from their shells, forming an ion, or shell electrons are excited to outer shells. Recombinational gamma spectra (electromagnetic) is produced and radiated in all directions, when the excited or ionized electrons fall into the inner shells.

Elastic Scattering – This lesser (secondary) radiation tends to possess lower energy content and is also radiated in all directions. The radiation intensity is an increasing function of the material's atomic number. This attribute is well suited for measuring coating thicknesses on base materials (having different atomic numbers to the coating) via backscattering techniques.

γ-Rays – Gamma rays (electromagnetic energy) are attenuated through reductions in their quanta energies, via the combined processes of photoelectric absorption, scattering and pair production (Hubble & Seltzer, 2004). The experienced attenuation is an exponential function of the inbound radiation energy spectra, and the material composition and thickness. This relationship makes this form of radiation an attractive choice for material thickness measurement via a knowledge of the applied radiation, the material composition and an examination of the resulting transmitted radiation.

4.2 Mass Attenuation Coefficient

The manner in which a composite / alloyed material responds to inbound photonic radiation can be characterized by the composite Mass Attenuation Coefficient (MAC), μ/ρ, of its elemental constituents (typically with units of (cm^2/g)). The MAC is a material density normalization of the Linear Attenuation Coefficient (LAC), μ, where ρ is the density of the material (in g/cm^3), and the MAC is therefore an energy dependent constant that is independent of physical state (solid, liquid, gas). The reciprocal of the LAC, q, is often termed the Mean Free Path. The MAC is typically characterized as an energy cross-section, with the amplitude of attenuation being a function of applied photonic energy, (Hubble & Seltzer, 2004). Figure 4.1 provides a graphical representation of the MAC for the element Iron (Fe, Atomic No.: 26). Radiation attenuation is composed of five(5) primary processes:

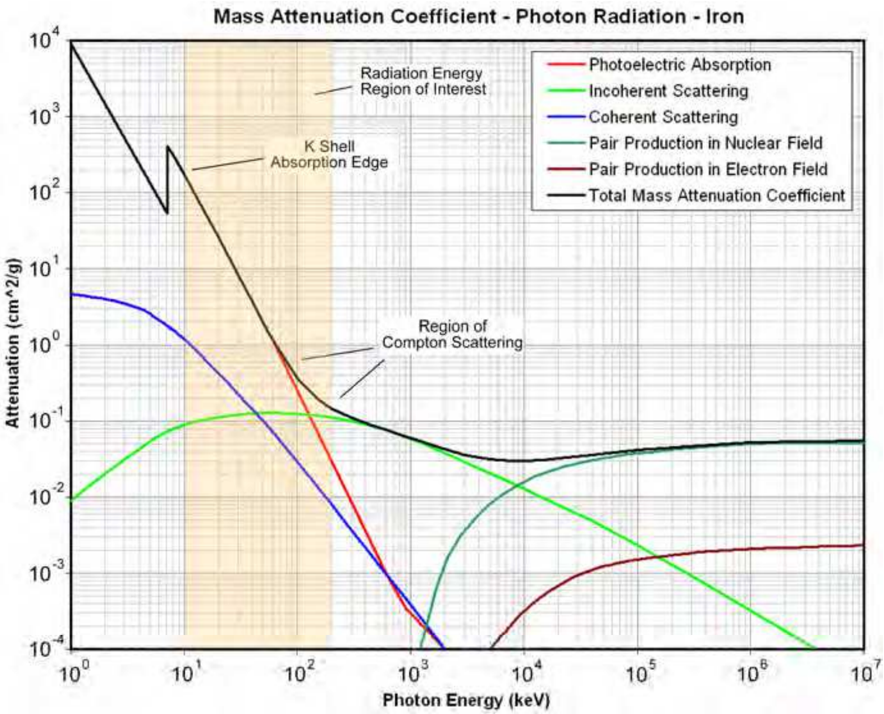


Fig. 4.1 – Graphical representations of the Mass Attenuation Coefficient, (μ/ρ), of the element Iron (Fe) as a function of the applied photonic energy.

<u>Photoelectric Absorption</u> – This process is in effect at lower energies and involves the conversion of the inbound photon's energy to the excitation of the material atom's inner shell electrons (K or L), beyond their binding energies and dislodging them from the atom, to form an ion (Mark & Dunn, 1985). These free electrons (photoelectrons) recombine with free ions and radiate with a characteristic spectra of the material's constituent atoms (recombinational spectral lines). This radiation is emitted in all directions in the form of an X-Ray fluorescence (whose energy increases with atomic number). If the inbound radiation energy is below shell's binding energy, photoelectrons are not formed from that shell and an abrupt decrease in the material's absorption characteristics is noted (see the abrupt, saw-tooth absorption edge in Figure 4.1).

Incoherent Scattering (Compton Scattering) – This absorption process is in effect over a broad range of energies, and involves inelastic scattering interactions between the material atom's electrons and the inbound photonic radiation (Kaplan, 1955). The electrons are transferred part of the inbound radiation energy (causing them to recoil) and a photon containing the remaining energy to be emitted in a different direction from the inbound, higher energy photon. The overall kinetic energy is not conserved (inelastic), but the overall momentum is conserved. If the released photon has sufficient energy, this process may be repeated. The Compton scatter radiation has a directional dependency that results in radiated lobes of having angular intensity dependencies.

Coherent Scattering (Rayleigh Scattering) – This absorption process is in effect in the lower energy regions, and involves the elastic scattering interactions between the inbound photons and physical particles that are much smaller than the wavelength of the photon energy, (Kaplan, 1955).

Pair Production – This absorption process is in effect only at very high energies (greater than twice the rest-energy of an electron (>1.022MeV)), and involves the formation of electron pairs (an electron and a positron), (Halliday, 1955). The electron pair converts any excess energy to kinetic energy, which may induce subsequent absorption / collisions with the material's atoms. This absorption process occurs only at very high energies, and therefore has no practical application in the forms of thickness measurement considered here.

The summation of these components forms the MAC and precision cross-section data is openly published as tabulated lists by the National Institute of Standards and Technology (NIST) (Hubble & Seltzer, 2004), for all the naturally occurring periodic table elements to an atomic number of 92 (Uranium).

It is important to examine the nature of the material absorption characteristics within the region of radiation energy of interest (10keV – 200keV), see Figure 4.1. Here, the attenuation characteristics of the lower energy section is dominated by the Photoelectric absorption. At energies higher than about 100keV, Compton Scattering becomes the primary method of attenuation.

Depending on the nature of a given element's atomic structure and atomic weight, the behavior of the MAC can vary widely. Figure 4.2 provides a comparative plot of four common elements, along with an indication of the energy level associated with the primary spectral line for Americium 241 (59.5keV). The key aspect of this comparison is the extent and energy regions involved in the differences in the attenuation characteristics. Carbon offers very little attenuation and only at low energies, while lead dominates the spectrum, especially at higher energies, illustrating its excellent shielding characteristics. Copper and iron have very similar behavior, and also show K Shell absorption edges at their distinct energies. The differences in attenuation between these metals appear to be relatively small, however, in the region about 60keV, copper has over 30% more attenuation than iron.

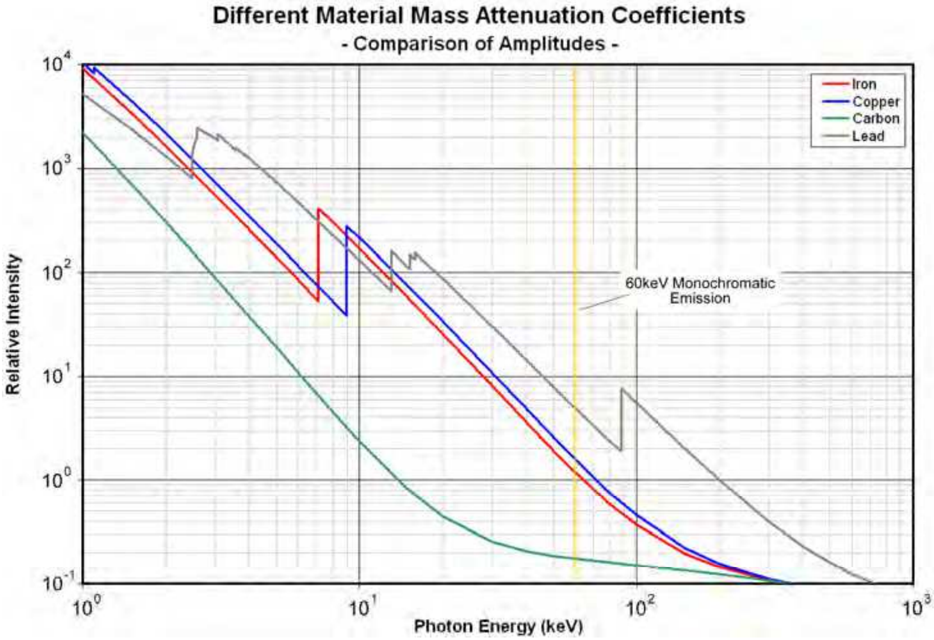


Fig. 4.2 – Graphical comparisons of the energy dependent MACs of differing materials and an indication of the location of 60keV incident radiation.

4.3 Attenuation Characterization

4.3.1 Monochromatic Beer-Lambert Law

When monochromatic radiation of known intensity, I_0, is attenuated by the material, the relationship to the resulting, transmitted radiation, I, is an exponential function of the MAC, the material density and thickness, originating from the differential form:

$$-\frac{dI}{I} = \mu\, dx = \frac{dx}{q} \tag{4.1}$$

where

- μ – Linear Absorption Coefficient (LAC - subject to material density variations)
- q – Mean Free Path (MFP – subject to density material variations)
- x – Material Thickness

Integrating Eq(4.1) results in:

$$I = I_0\, e^{-\mu x} = I_0\, e^{-\frac{x}{q}} \tag{4.2}$$

Expanding Eq(4.2) to employ the MAC, , produces the Beer-Lambert Law (Halliday, 1955), (Kaplan, 1955):

$$I = I_0 e^{-\left(\frac{\mu}{\rho}\right)\rho x} = I_0 e^{-\frac{x}{q}} \tag{4.3}$$