Irradiation of Food

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Irradiation of Food

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KEY TERMS

Radiation sources
Absorbed dose
Depth-dose distribution
Ionizing radiation effect
Food safety applications
Kinetics of pathogen inactivation

Variables

λ = wavelength
η = throughput efficiency
ρ = density of irradiated material
A_c = cross-sectional area of food or package
A_d = aerial density
c = speed of light in a vacuum (3.0×10^8 m/s)
C = rate of energy loss for e-beam treatment in water and water-like issues (2.33 MeV/cm)
dE = energy in infinitesimal volume dv
dm = mass in infinitesimal volume dv
dm/dt = throughput or amount of product per time
d_p = penetration depth of radiation energy per unit area
d = thickness (or depth) of food
d_{opt} = depth at which maximum throughput efficiency occurs for one-sided irradiation
D = applied or absorbed dose or energy per unit mass
D_{10} = radiation D value or kGy required to inactivate 90% of microbial population
D_{max} = maximum dose
D_{min} = minimum dose

D_{sf} = front surface dose, defined as the dose delivered at a depth d into the food, the target dose
DUR = dose uniformity ratio
E = maximum absorbed energy
E_{50} = E_{mean} = absorbed energy at a depth of r_{50}
E_{ab} = energy deposited per incident electron
E_{p} = energy of a photon
f = radiation frequency
h = Planck's constant (6.626×10^{-34} J·s)
I_{a} = average current
I''_{A} = current density
k = exponential rate constant
m = mass of food
N = microbial population at a particular dose
N_0 = initial microbial population
P = machine power
r_{max} = depth at which the maximum dose occurs
r_{opt} = depth at which the dose equals the entrance dose
r_{33} = depth at which the dose equals a third of the maximum dose
r_{50} = depth at which the dose equals half of the maximum dose
t = irradiation time
v = speed
w = scan width

Introduction

Food irradiation is a non-thermal technology often called "cold pasteurization" or "irradiation pasteurization" because it does not increase the temperature of the food during treatment (Cleland, 2005). The process is achieved by treating food products with ionizing radiation. Other common non-thermal processing technologies include high hydrostatic pressure, high-intensity pulsed electric fields, ultraviolet (UV) light, and cold plasma.

Irradiation technology has been in use for over 70 years. It offers several potential benefits, including inactivation of common foodborne bacteria and inhibition of enzymatic processes (such as those that cause sprouting and ripening); destruction of insects and parasites; sterilization of spices and herbs; and shelf life extension. The irradiation treatment does not introduce any toxicological, microbiological, sensory, or nutritional changes to the food products (packaged and unpackaged) beyond those brought about by conventional food processing techniques such as heating (vitamin degradation) and freezing (texture degradation) (Morehouse and Komolprasert, 2004). It is the only commercially available decontamination technology to treat fresh and fresh-cut fruits and vegetables, which do not undergo heat treatments such as pasteurization or sterilization. This is critical because many recent foodborne illness outbreaks and product recalls have been associated with fresh produce due to contamination with *Listeria*, *Salmonella*, and *Escherichia coli*. Approximately 76 million illnesses, 325,000 hospitalizations, and 5000 deaths occur in the United States annually and 1.6 million illnesses, 4000 hospitalizations, and 105 deaths in Canada (Health Canada, 2016). During 2018, these outbreaks caused 25,606 infections, 5,893 hospitalizations, and 120 deaths in the US (CDC, 2018).

Irradiation of foods has been approved by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations. At least 50 countries use this technology today for treatment of over 60 products, with spices and condiments being the largest application. In 2004, Australia became the first country to use irradiation for phytosanitary purposes, i.e., treatment of plants to control pests and plant diseases for export purposes (IAEA, 2015; Eustice, 2017). About ten countries have established bilateral agreements with the United States for trade in irradiated fresh fruits and vegetables. More than 18,000 tons of agricultural products are irradiated for this purpose around the world. The US has a strong commercial food irradiation program, with approximately 120,000 tons of food irradiated annually. Mexico, Brazil, and Canada are also big producers of irradiated products. China is the largest producer of irradiated foods in Asia, with more than 200,000 tons of food irradiated in 2010 (Eustice, 2017) followed by India, Thailand, Pakistan, Malaysia, the Philippines, and South Korea. Egypt and South Africa use irradiation technology to treat spices and dried foods. Russia, Costa Rica, and Uruguay have obtained approval for irradiation treatment of foods. Eleven European Union countries utilize food irradiation but the rest have been reluctant to adopt the technology due to consumers' misconceptions, such as thinking that irradiated foods are radioactive with damaged DNA or "dirty" (Maherani et al., 2016).

Food irradiation can be accomplished using different radiation sources, such as gamma rays, X-rays, and electron beams. Although the basic engineering principles apply to all the different sources of radiation energy, this chapter focuses on high-energy electron beams and X-rays to demonstrate the concepts because they are a more environmentally acceptable technology than the cobalt-60-based technology (gamma rays).

Outcomes

After reading this chapter, you should be able to:

- Explain the interaction of ionizing radiation with food products
- Quantify the effect of ionizing radiation on microorganisms and determine the dose required to inactivate pathogens in foods
- Select the best irradiation approach for different food product characteristics

Concepts

Food irradiation involves using controlled amounts of ionizing radiation with enough energy to ionize the atoms or molecules in the food to meet the desired processing goal. *Radiation* is the emission of energy that exists in the form of waves or photons as it travels through space or the food material (electromagnetic energy). In other words, it is a mode of energy transfer. The heat transfer equivalent would be the energy emitted by the Sun.

The type of radiation used in food processing is limited to high-energy gamma rays, X-rays, and accelerated electrons or electron beams (e-beams). Gamma and X-rays form part of the electromagnetic spectrum (like radio waves, microwaves, ultraviolet, and visible light rays), occurring in the short wavelength (10^{-8} to 10^{-15} m), higher frequency (10^{16} to 10^{23} Hz), high-energy (10^{2} to 10^{9} eV) region of the spectrum. High-energy electrons produced by electron accelerators in the form of e-beams can have as much as 10 MeV (megaelectronvolts = eV × 10^6) of energy (Browne, 2013).

The wavelength, or distance between peaks, λ, of the radiation energy is defined as the ratio of the speed of light in a vacuum, c, to the frequency, f, as follows:

$$\lambda = \frac{c}{f} \tag{1}$$

where λ = wavelength (m)

$c = 3.0 \times 10^8$ (m/s)

f = radiation frequency (1/s)

From a quantum-mechanical perspective, electromagnetic radiation may be considered to be composed of photons (groups or packets of energy that are quantified). Therefore, each photon has a specific value of energy, E, that can be calculated as follows:

$$E_p = hf \tag{2}$$

where E_p = energy of a photon (J)

h = Planck's constant (6.626×10^{-34} J·s)

f = radiation frequency (1/s)

The frequency, energy and wavelength of different types of electromagnetic radiation, calculated using equations 1 and 2, are given in table 1. The higher the frequency of the electromagnetic wave, the higher the energy, and the shorter the wavelength. Table 1 illustrates that X-rays and gamma rays are used in food irradiation processes because of their high energy. Table 1 also explains why exposure to UV light would only cause sunburn (lower energy electromagnetic radiation) while exposure to X-rays could be lethal (high-energy electromagnetic radiation).

Radiation Sources and Their Interactions with Matter

The properties and effects of gamma rays and X-rays on materials are the same, but their origins are different. X-rays are generated by machines while gamma rays come from the spontaneous disintegration of radionuclides, with cobalt-60 (^{60}Co) the most commonly used in food processing applications. X-ray machines with a maximum energy of 7.5 MeV and electron accelerators with a maximum energy of 10 MeV are approved by WHO worldwide because the energy from these radiation sources is too low to induce radioactivity in the food product (Attix, 1986). Likewise, although gamma rays are high energy radiation sources, the doses approved for irradiation of foods do not induce any radioactivity in products.

The difference in nature of the types of ionizing radiation results in different capabilities to penetrate matter (table 2). Gamma-ray and X-ray radiation can penetrate distances of a meter or more into the product, depending on the product density, whereas electron beams (e-beams), even with energy as high as 10 MeV, can penetrate only several centimeters. E-beam accelerators range from 1.35 MeV to 10 MeV (Miller, 2005). All types of radiation become less intense the further the distance from the radioactive material, as the particles or rays become more spread out (USNRC, 2018).

Table 1. Frequency, energy level and wavelength of the different types of electromagnetic radiation calculated using equations 1 and 2.

Type of Electromagnetic Radiation	Frequency, *f* (Hz)	Energy, *E* (eV)	Wavelength, λ (cm)
Gamma rays	1020	4.140×10^5	3.0×10^{-10}
X-rays	1018	4.140×10^2	3.0×10^{-8}
UV light	1016	4.140	3.0×10^{-6}
Infrared light	1014	0.414	3.0×10^{-4}

Table 2. Different types of radiation sources and their characteristics (Attix, 1986; Lagunas-Solar, 1995; Miller, 2005).

	Source		
Characteristics	E-beams	X-rays	Cobalt-60 (gamma rays)
Energy (MeV)	10	5 or 7.5	1.17 and 1.33
Penetration depth (cm)	< 10	100	70
Irradiation on demand (machine can be turned off)	yes	yes	no
Relative throughput efficiency	high	medium	low
Dose uniformity ratio (D_{max}/D_{min})	low	high	medium
Administration process	authorization required[a]	authorization required[a]	authorization required[b]
Treatment time	seconds	minutes	hours
Average dose rate (kGy/s)	~3	0.00001	0.000061
Applications	low density products can be treated in cartons	low/medium density products can be treated in cartons or pellets	low/medium density products can be treated in cartons or pellets

[a] Standard registration required

[b] Complex and difficult process with extensive training

Absorbed Dose

Absorbed dose, or dose, *D*, is the quantity of ionizing radiation imparted to a unit mass of material. This quantity is used both to specify the irradiation process and to control it to ensure the product is not over- or under-exposed to the radiation energy. In food irradiation operations, dose values are average values because it is difficult to measure dose in small materials (IAEA, 2002).

The SI unit of absorbed dose is the gray (Gy), where 1 Gy is equivalent to the absorption of 1 J per kg of material. Therefore, absorbed dose at any point in the target food is expressed as the mean energy, dE, imparted by ionizing radiation to the matter in an infinitesimal volume, dv, at that point divided by the infinitesimal mass, m, of dv:

$$D = \frac{dE}{dm} \tag{3}$$

where D = dose (Gy)
dE = energy in infinitesimal volume dv (J)
dm = mass in infinitesimal volume dv (kg)

D represents the energy per unit mass which remains in the target material at a particular point to cause any effects due to the radiation energy (Attix, 1986).

In 1928, the roentgen was conceived as a unit of exposure, to characterize the radiation incident on an absorbing material without regard to the character of the absorber. It was defined as the amount of radiation that produces one electrostatic unit of ions, either positive or negative, per cubic centimeter of air at standard temperature and pressure (STP). In modern units, 1 roentgen equals 2.58×10^{-4} coulomb/kg air (Attix, 1986). In 1953, the International Commission on Radiation Units and Measurements (ICRU) recommended the “rad” as a new unit with 1 Gy equal to 100 rad. The term “rad” stands for “radiation absorbed dose.” Absorbed dose requirements for various treatments involving food products range from 0.1 kGy to 30 kGy (table 3). Table 4 shows the maximum allowable dose for different products in the United States and worldwide.

Table 3. Absorbed dose requirement for different food treatments (IAEA, 2002).

Treatment	Absorbed Dose (kGy)[a]
Sprout inhibition	0.1–0.2
Insect disinfestation	0.3–0.5
Parasite control	0.3–0.5
Delay of ripening	0.5–1
Fungi control	0.5–3
Pathogen inactivation	0.5–3
Pasteurization of spices	10–30
Sterilization (pathogen inactivation)	15–30

[a] 1 kGy = 10^3 Gy

Table 4. Maximum allowable dose for different foods in the United States and worldwide (WHO, 1981; ICGFI, 1999; Miller, 2005).

Purpose	Maximum Dose (kGy)	Product
Disinfestation	1.0	any food
Sprout inhibition	0.1–0.2	onions, potatoes, garlic
Insect disinfestation	0.3–0.5	fresh dried fruits, cereals and pulses, dried fish and meat
Parasite control	0.3–0.5	fresh pork
Delay of ripening	0.5–1.0	fruits and vegetables
Pathogen inactivation	3.0	poultry, shell eggs
Pathogen inactivation	1.0	fresh fruits and vegetables
Pathogen inactivation	4.5–7.0	fresh and frozen beef and pork
Pathogen inactivation	1.0–3.0	fresh and frozen seafood
Shelf life extension	1.0–3.0	fruits, mushrooms, leafy greens
Pasteurization	10–30	spices
Commercial sterilization	30–50	meat, poultry, seafood, prepared foods, hospital foods, pet foods

The dose rate, or amount of energy emitted per unit time (dD/dt or $\frac{d}{dt}\left(\frac{dE}{dm}\right)$), determines the processing times and, hence, the throughput of the irradiator (i.e., the quantity of products treated per time unit). In those terms, 10 MeV electrons can produce higher throughput (higher dose rate) compared to X-rays and gamma rays (table 2). Similar to absorbed dose, dose rates are average values.

Depth-Dose Distribution and Electron Energy

The energy deposition profile for a 10 MeV e-beam incident onto the surface of a water absorber has a characteristic shape (figure 1). The y-axis is the energy deposited per incident electron per unit area, E, also described as E_{ab}. This parameter is proportional to the absorbed dose, D. The x-axis is the penetration depth (also called mass thickness), d, in units of area density, g/cm^2, which is the thickness in cm multiplied by the volume density in g/cm^3:

$$d_p = d\rho \qquad \textbf{(4)}$$

where d_p = penetration depth of radiation energy per unit area (g/cm^2)

d = thickness of irradiated material (cm)

ρ = density of irradiated material (g/cm^3)

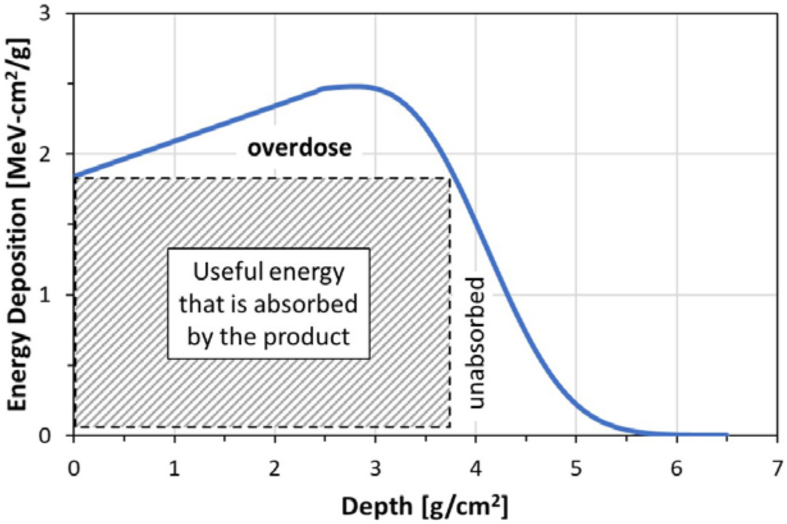

Figure 1. Energy deposition profile for 10 MeV electrons in a water absorber (adapted from Miller, 2005).

The penetration depth, d, of ionizing radiation is defined as the depth at which extrapolation of the tail of the dose-depth curve meets the x-axis (approximately 6 g/cm^2 in figure 1). Figure 1 also shows how the dose, D, tends to increase with increasing depth within the product to about the midpoint of the electron penetration range and then it quickly falls to low doses.

Because the electron energy deposition is not constant, there is a location in the product that will receive a minimum dose, D_{min}, and another position that will receive the maximum dose, D_{max}. A useful parameter for irradiator designers and engineers is the dose uniformity ratio (*DUR*), defined as the ratio of maximum to minimum absorbed dose:

$$DUR = \frac{D_{max}}{D_{min}} \qquad \textbf{(5)}$$

A *DUR* close to 1.0 represents uniform dose distribution in the sample (Miller, 2005; Moreira et al., 2012). However, values greater than 1.0 are common in commercial applications and many food products can tolerate a higher *DUR*, of 2 or even 3 (IAEA, 2002).

The absorbed dose, *D*, at a particular depth, *d*, can be calculated as the product of the energy deposited times the current density times the irradiation time (Miller, 2005):

$$D(d) = E_{\mathrm{ab}} I''_{\mathrm{A}} t \tag{6}$$

where D = dose (MeV/g) (1 Gy = 6.24×10^{12} MeV/kg)
E_{ab} = energy deposited per incident electron (MeV-cm^2/g)
I''_{A} = current density (A/cm^2)
t = irradiation time (s)

For a product with thickness, *x*, the energy represented by the dashed area in figure 1 is the useful energy absorbed in the product. The maximum efficiency will occur when the product depth is such that the back surface of the target product receives the same dose as the top surface. For instance, using figure 1 and assuming only energy penetration through the thickness of the material, the target with a minimum dose of 1.85 MeV/g (entrance dose) and the optimum depth of 3.8 g/cm^2 represents an effective absorbed energy of about 7 MeV (= 1.85 × 3.8). Therefore, using 10 MeV e-beams, the maximum utilization efficiency is 70% (Miller, 2005).

The depth in g/cm^2 at which the maximum throughput efficiency occurs for one-sided irradiation can be calculated as (Miller, 2005):

$$Depth_{\mathrm{optimum}} = d_{\mathrm{opt}} = 0.4 \times E - 0.2 \tag{7}$$

where E is the maximum absorbed energy (MeV).

Equation 7 provides a useful measure of the electron penetration power of the irradiator. The penetration of high-energy e-beams in irradiated materials increases linearly with the incident energy. The electron range (penetration) also depends on the atomic composition of the irradiated material. Materials with higher electron contents (electrons per unit mass) will have higher absorbed doses near the entrance surface, but lower electron ranges (penetration). For instance, because of its lack of neutrons, hydrogen has twice as many atomic electrons per unit mass as any other element. This means that materials with higher hydrogen contents, such as water (H_2O) and many food products, will have higher surface doses and shorter electron penetration than other materials (Becker et al., 1979).

In general, dose-penetration depth curves, such as the one represented by figure 1, show an initially marked increase (buildup) of energy deposition near the surface of the irradiated product. This buildup region is a phenomenon that happens in materials of low atomic number due to the progressive cascading of secondary electrons by collisional energy losses (IAEA, 2002). This is then followed by an exponential decay of dose to greater depths. The approximate value of the buildup depth for gamma rays (1.25 MeV) is 0.5 cm of water, while the depth for 10 MeV e-beams is 10.0 cm of water (IAEA, 2002).

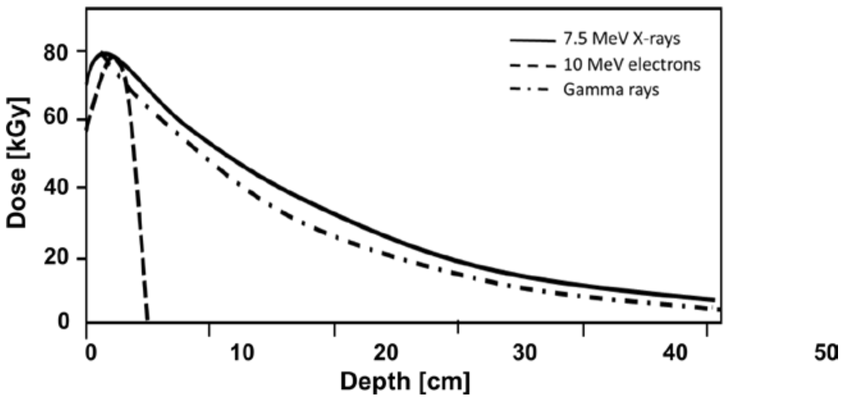

Figure 2. Dose-depth penetration for different radiation sources (X-rays, electron beams, and gamma rays) (adapted from IAEA, 2015).

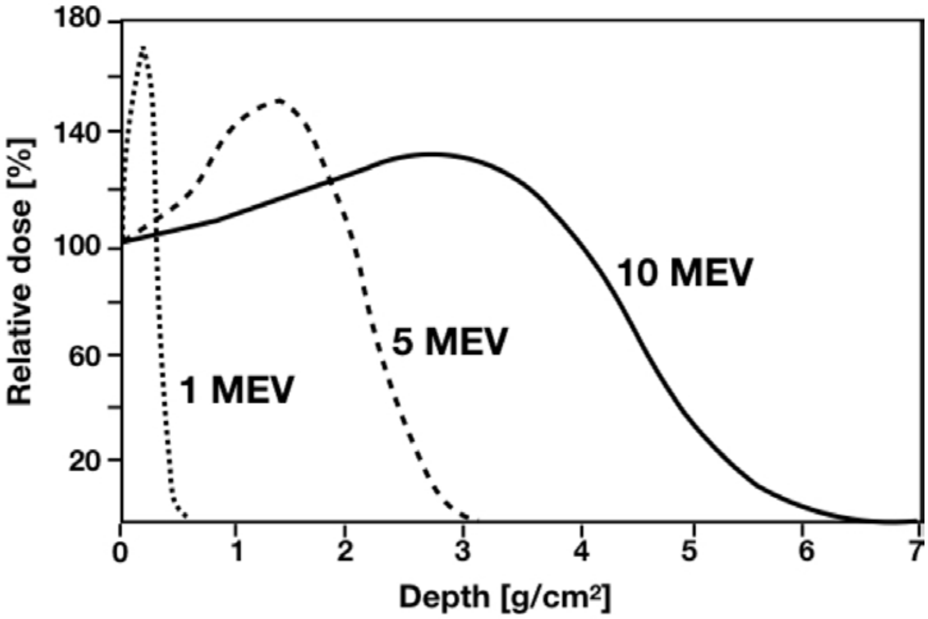

Figure 3. Typical depth-dose curves for electrons of various energies in the range applicable to food processing operations (adapted from IAEA, 2002). Here depth is penetration depth per unit area, d_p.

Figure 2 shows the point of maximum dose (in kGy) and the absorption of energy for both electrons and photons (X-rays and gamma rays). The penetration depth of 10 MeV e-beams is limited as they deposit their energy over a short depth, with a maximum located after the entrance point. In the case of gamma rays, the energy is deposited over a longer distance, which results in a uniform dose distribution within the treated product. The penetration capabilities of both 7.5 MeV X-rays and gamma rays are comparable, but the higher energy of the X-rays results in a slightly more uniform distribution of the doses within the treated product. The configuration of the product strongly influences dose distribution within the product (IAEA, 2002).

Figure 3 shows the depth-dose distributions in water-equivalent products (such as fruits and vegetables) ranging from 1 to 10 MeV in terms of *relative dose* in percentage. For instance, for the 10 MeV curve, if the entrance (at the surface) dose of 1 kGy is 100%, the relative dose at a depth of 1 cm^2/g is approximately 110% of the entrance dose or 1.1 kGy, and it is 0 and 1.40 kGy for 1 MeV and 5 MeV irradiation systems, respectively.

The shapes of the depth-dose curves shown in figure 3 can be better defined in terms of the penetration depth within the product (or product thickness) (figure 4). The parameters defined in figure 4, r_{max}, r_{opt}, r_{50}, and r_{33}, are useful to determine the maximum product thickness that can be irradiated using a particular type of electron beam (1, 5, or 10 MeV). Additionally, the deposited energy can be determined at a specific depth. For instance, E_{50} at a depth of r_{50} = 4.53 cm in water for a 10 MeV irradiation system is,

$$E_{\text{mean}} = E_{50} = Cr_{50} = 2.33(4.53\,\text{cm}) = 10.55\,\text{MeV} \quad \textbf{(8)}$$

where C is the rate of energy loss for e-beam treatment in water and water-like tissues = 2.33 MeV/cm (Strydom et al., 2005).

From figure 4 with r_{max} equal to 2.8 cm, the maximum dose is 130% or 1.3 kGy, and the entrance dose equals the exit dose at r_{opt} equal to 4 cm. This result means that if the irradiated product has a thickness between 2.8 and 4 cm, the *DUR* is constant with a value of 1.3 (*DUR* = 1.3 kGy/1.0 kGy). Such a *DUR* value suggests the irradiation process provides good uniformity in the dose distributed throughout the product thickness. If the process yields a *DUR* of 2 with a minimum dose of 0.67 kGy (*DUR* = 1.35 kGy/0.67 kGy), the maximum useful thickness of the irradiated product will be 4.5 cm or r_{50}, the depth at which the dose is half the maximum dose.

Note that $r_{50} > r_{\text{opt}}$. Hence, if the product thickness exceeds r_{opt}, the *DUR* increases. As *DUR* approaches infinity at a depth of 6.5 cm for 10 MeV e-beam (figure 4), any part of the product beyond that depth will remain unexposed to the irradiation treatment. Therefore, the maximum processable product thickness for this irradiation system will be 6.5 cm. This result highlights a critical issue when using electron beam accelerators to pasteurize or sterilize food products, which need to be exposed in their entirety to the radiation energy.

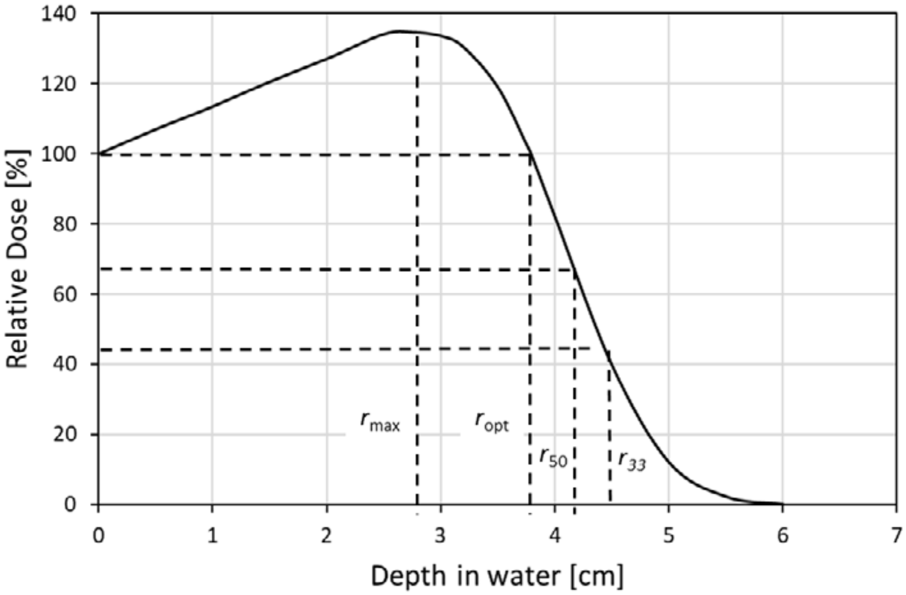

Figure 4. Depth-dose curve for 10 MeV electrons in water, where the entrance (surface) dose is 100% (adapted from IAEA, 2002). r_{max} is the depth in cm at which the maximum dose occurs, r_{opt} is the depth at which the dose equals the entrance dose (also described by equation 7), r_{50} is the depth at which the dose equals half of the maximum dose, and r_{33} is the depth at which the dose equals a third of the maximum dose.

The engineer has the option to apply the e-beams using the single e-beam configuration (which exposes the target food only on the top or bottom surface) or the double-beam configuration (which exposes the target food at both the top and bottom surfaces). Figure 5 illustrates the difference between one-sided and two-sided irradiation systems using 10 MeV electrons in water when *DUR* is 1.35.

Figure 5 shows that when irradiating from the top or bottom only, the maximum processable thickness will be close to 4 cm (shaded areas, figure 6), while the double-beam system increases the maximum processable thickness to about 8.3 cm (shaded area, figure 7). Therefore, to improve the penetration capability of a 10 MeV e-beam treatment, two 10 MeV accelerators, one irradiating from the top and the other from the bottom of a conveyor system, are frequently used in commercial applications (IAEA, 2002).

The depth at which the maximum throughput efficiency occurs for double-sided irradiation can be calculated as (Miller, 2005):

$$Depth_{\text{optimum}} = d_{\text{opt}} = 0.9 \times E - 0.4 \qquad \textbf{(9)}$$

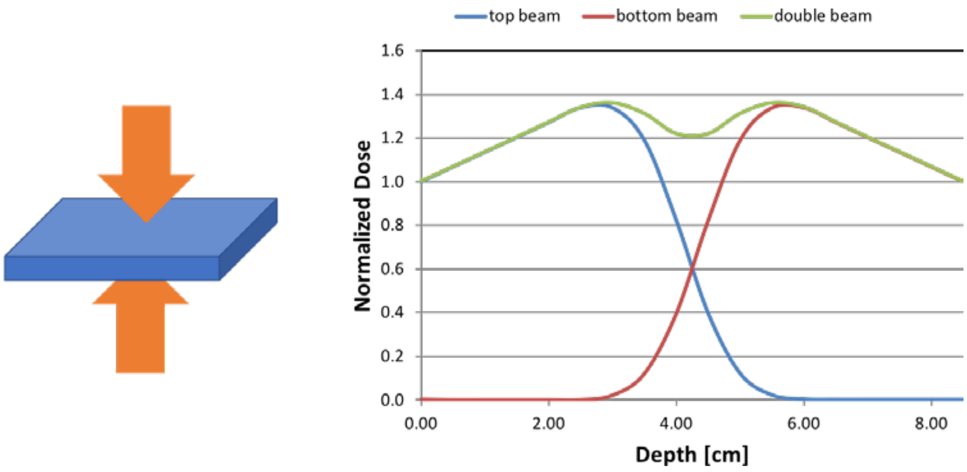

Figure 5. Depth-dose distributions for 10 MeV electrons in water for single-sided and double-sided configurations and *DUR* = 1.35. Normalized dose is the ratio of maximum to entrance dose (Miller, 2005).

Measurement of Absorbed Dose

The effectiveness of ionizing radiation in food processing applications depends on proper delivery of the absorbed dose. To design the correct food irradiation process, the operator should be able to (1) measure the absorbed dose delivered to the food product using reliable dosimetry methods; (2) determine the dose distribution patterns in the product package; and (3) control the routine radiation process (through process control procedures). Dosimeters are used for quality and process control in radiation research and commercial processing.

Reliable techniques for measuring dose, called *dosimetry*, are crucial for ensuring the integrity of the irradiation process. Incorrect dosimetry can result in an ineffective food irradiation process. Dosimetry systems include physical or chemical dosimeters and measuring instrumentation, such as spectrophotometers and electron paramagnetic resonance (EPR) spectrometers. A *dosimeter* is a device capable of providing a reading that is a measure of the absorbed dose, *D*, deposited in its sensitive volume, *V*, by ionizing radiation. The measuring instrument must be well characterized so that it gives reproducible and accurate results (Attix, 1986).

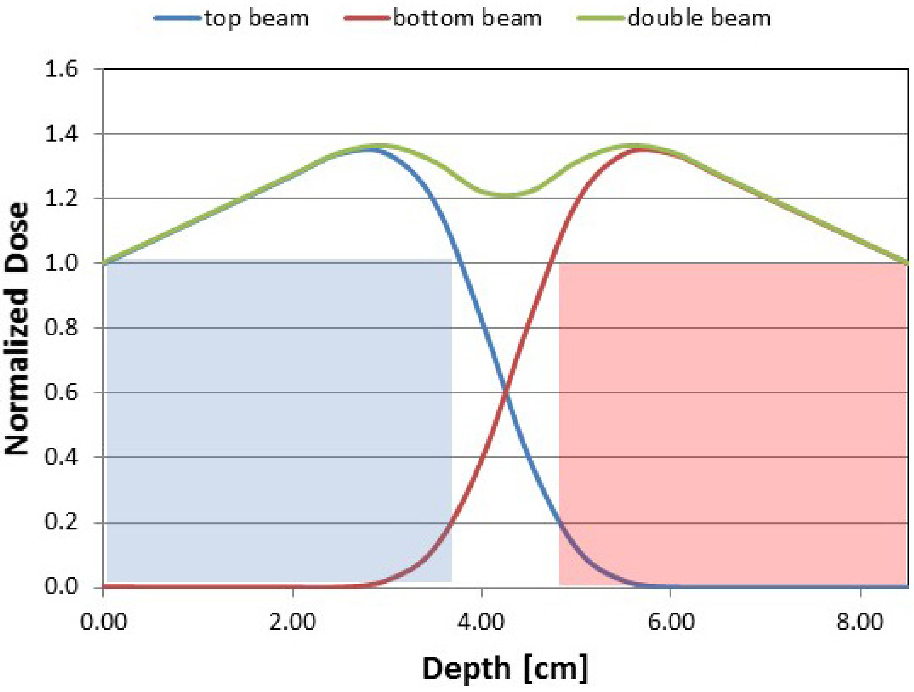

Figure 6. Maximum penetration thickness for top-only and bottom-only e-beam configurations using 10 MeV electrons in water and *DUR* = 1.35.

There are four categories of dosimetry systems according to their intrinsic accuracy and usage (IAEA, 2002):

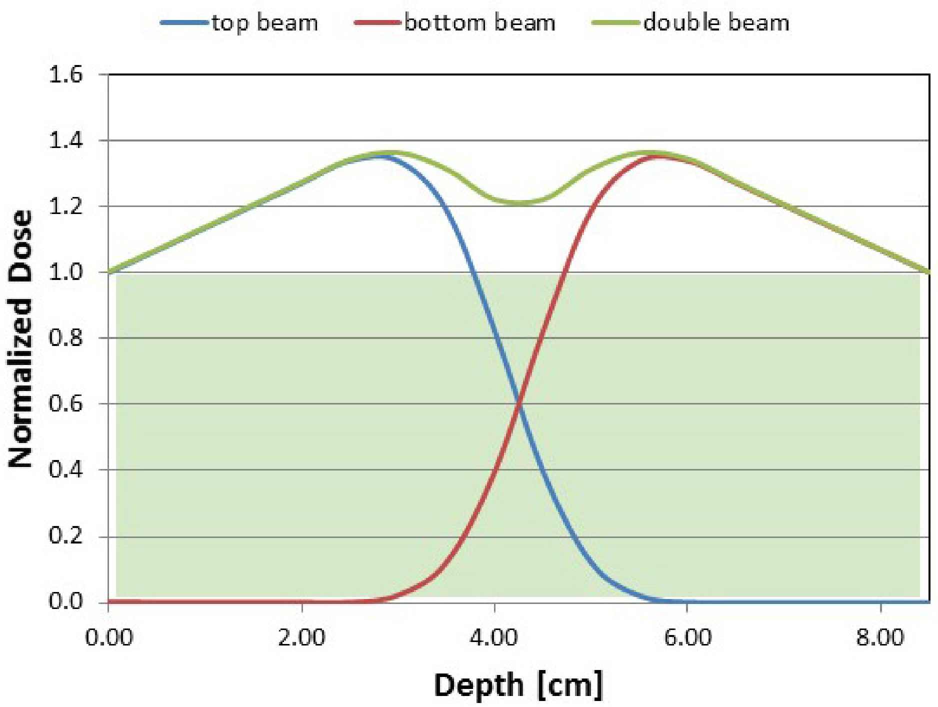

Figure 7. Maximum penetration thickness for double-sided e-beam irradiation using 10 MeV electrons in water (*DUR* = 1.35).

- *Primary standards* (ion chamber, calorimeters) measure the absolute (i.e., does not need to be calibrated) absorbed dose in SI units.
- *Reference standards* (alanine, Fricke, and other chemicals) have a high metrological quality that can be used as a reference standard to calibrate other dosimeters. They need to be calibrated against a primary standard, generally through the use of a transfer standard dosimeter.
- *Transfer standards* (thermoluminiscent dosimeter, TLD) are used for transferring dose information from a national standards laboratory to an irradiation facility to establish traceability to that standards laboratory. They should be used under conditions specified by the issuing laboratory. They need to be calibrated.
- *Routine dosimeters* (process monitoring, radiochromic films) are used in radiation processing facilities for dose mapping and for process monitoring for quality control. They must be calibrated frequently against reference or transfer dosimeters.

The main pathogenic microorganisms of concern in food processing are *Salmonella* spp., *Escherichia coli* and *Listeria* spp. The abbreviation “spp.” stands for more than one species in that genus, here meaning there are several types of bacteria in the same group.

Food Irradiation and Food Safety Applications

Effect of Ionizing Radiation on Pathogens

Pathogen inactivation is the end effect of food irradiation. Exposure to ionizing radiation has two main effects on pathogenic microorganisms. First, the radiation energy can directly break strands (single or double) of the microorganism’s DNA. The second effect occurs indirectly when the energy causes radiolysis of water to form very reactive hydrogen (H+) and hydroxyl (•OH) radicals. These radicals can recombine to produce even more reactive radicals such as superoxide (HO_2), peroxide (H_2O_2), and ozone (O_3), which have an important role in inactivating pathogens in foods. Although DNA is the main target, other bioactive molecules, such as enzymes, can likewise undergo inactivation due to radiation damage, which enhances the efficacy of the irradiation treatment.

Kinetics of Pathogen Inactivation

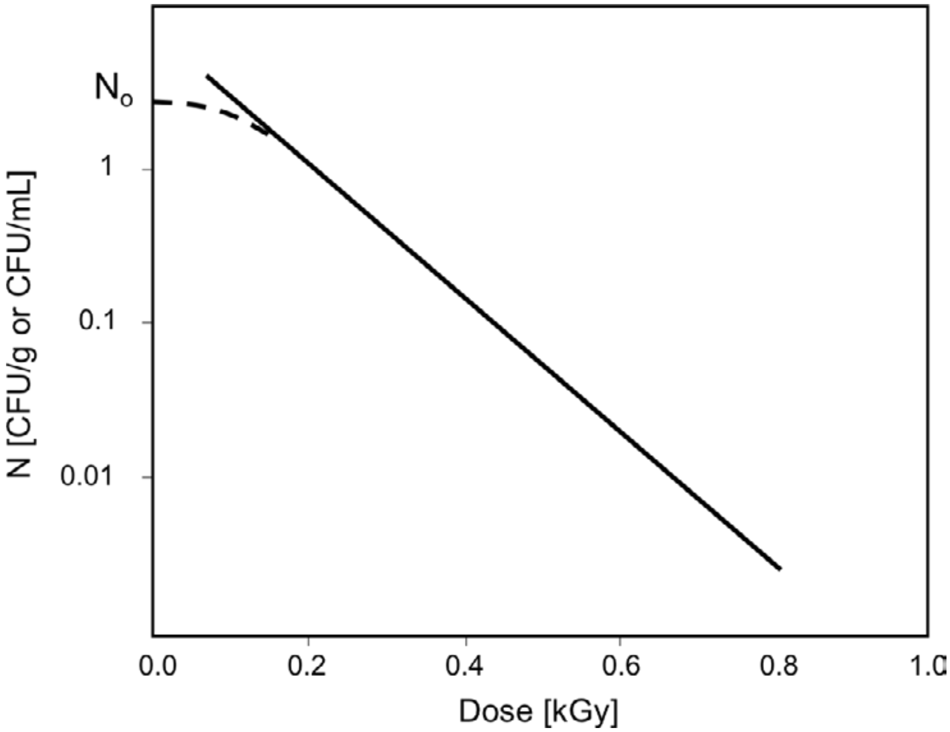

Figure 8. Typical survival curve showing first-order kinetics behavior with N_0 = initial microbial population and N = microbial population at a particular dose, both in CFU/g or CFU/mL. Dashed curve is initial nonlinear section of the curve.

The traditional approach used in thermal processing calculations is to develop survival curves, which are semilog plots of microorganism populations as a function of time at a given process temperature. This same approach can be used to develop radiation survival curves, i.e., plots of the log of the change in microbial populations as a function of applied dose. In this chapter, only first-order kinetics of microbial destruction are described.

Figure 8 is a survival curve obtained for inactivation of a pathogen in a food product due to exposure to radiation energy. Based on first-order kinetics (i.e., ignoring the initial non-linear section of the curve indicated by the arrow and the dashed line in figure 8), the microbial inactivation rate is described by:

$$\frac{dN}{dD} = -kD \qquad \textbf{(10)}$$

where N = microbial population at a particular dose (CFU/g or CFU/mL; CFU stands for colony forming units)
D = the applied dose (kGy)
k = exponential rate constant (1/kGy)

The radiation resistance of the target microorganism is usually reported as the radiation D value, D_{10}, defined as the amount of radiation energy (kGy) required to inactivate 90% (or one log reduction) of the specific microorganism (Thayer et al., 1990). Using this definition and integrating equation 10 yields:

$$N = N_0 e^{-kD_{10}} \qquad \textbf{(11)}$$

where N_0 = initial microbial population (CFU/g or CFU/mL)

Based on figure 8 and equation 11, the inverse of the slope of the line is the D_{10} value and is equivalent to the D-value used in thermal process calculations except that these have units of time as the slope of population change versus process time. The relationship between the D_{10} value and the rate constant is:

$$k = \frac{1}{D_{10}} \qquad \textbf{(12)}$$

The D_{10} value varies with the target pathogen, type and condition of food (whole, shredded, peeled, cut, frozen, etc.), and the atmosphere in which it is packed (e.g., vacuum-packaged foods, pH, moisture, and temperature) (Niemira, 2007; Olaimat and Holley, 2012; Moreira et al., 2012). For instance, the D_{10}-values for *Salmonella* spp. and *Listeria spp.* in fresh produce can range between 0.16 to 0.54 kGy while *Escherichia coli* is slightly more resistant to irradiation treatment (sometimes up to 1 kGy) (Fan, 2012; Rajtowski et al., 2003). When tomatoes are irradiated, the D_{10}-values for *Escherichia coli* O157:H7, *Salmonella* spp., and *Listeria monocytogenes* are around 0.39, 0.56, and 0.66 kGy, respectively (Mahmoud et al., 2010). In commercial applications, the rule of thumb is to design an irradiation treatment for a five log or $5D_{10}$ reduction in the population of the target pathogen.

Applications

The goal of a food irradiation process is to deliver the minimum effective radiation dose to all portions of the product. Too high a dose (or energy) in any region of the target product could lead to wasted energy and deterioration of product quality.

To design a food irradiation process, the absorbed dose in the material of interest must be specified because different materials have different radiation absorption properties. In the case of food products, the material of interest is water because most foods behave essentially as water regardless of their water content. Dose requirements and maximum allowable doses should be used for specific applications (tables 3 and 4).

Cost estimates for food irradiation facilities include the capital cost of equipment, installation and shielding, material handling and engineering, and variable costs including electricity, maintenance, and labor. The approximate cost of an e-beam accelerator facility for a production rate of 2000 hours per year is between 2 and 5 million US dollars and has remained fairly steady (Morrison, 1989; Miller, 2005; University of Wisconsin, 2019).

Technology Selection

The selection of the right technology for a particular food irradiation application depends on many factors, including food product characteristics and processing requirements (Miller, 2005). Figure 9 shows the steps required to choose a food irradiation approach.

The first step is to define the product characteristics. What is the main goal of the process? What is the product state, i.e., frozen, unpackaged, etc.? What is the product's density, shape, and mass flow rate going through the accelerator?

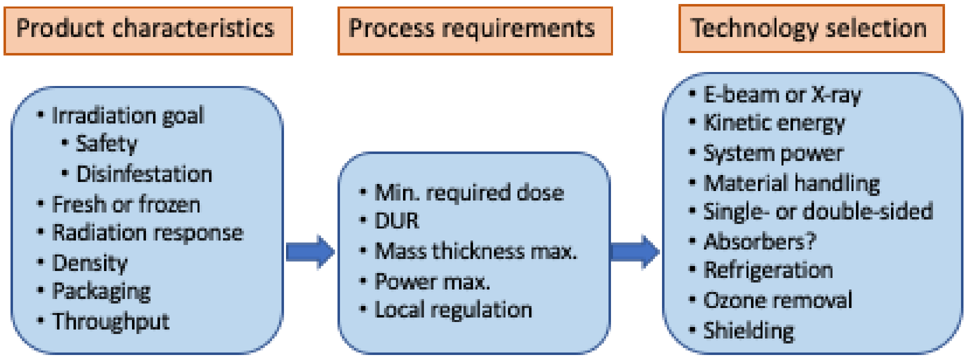

Figure 9. Steps needed to select the right irradiation technology for a food processing application (adapted from Miller, 2005).

The second step specifies the process requirements, including the product thickness and the acceptable *DUR* (equation 5). The final step is to select the appropriate radiation technology based on the product characteristics and process requirements. Selection includes determining the best technology (e-beams versus X-rays versus gamma rays), the size of the e-beam or X-rays accelerator(s), and, in the case of e-beams, whether single- or double-beam treatment will be more effective.

A simplified flow diagram provides guidelines to follow in selecting the right technology for food irradiation (figure 10). The engineer must first determine if the product could be effectively irradiated at all based on maximum to minimum dose ratios and energy efficiency concepts. The penetration depth depends on the product mass thickness (g/cm^2), which is based on the product and/or package dimensions and density (equation 4). For food safety treatments, the *DUR* is based on the minimum dose requirement to reduce the population of a certain pathogen (i.e., the D_{10} value, equation 12) and the maximum dose allowed by local regulation or the dose a product can tolerate without degrading its quality. As indicated in figure 10, in general, the product will not be suitable for irradiation treatment when its mass thickness is greater than 50 g/cm^2 and *DUR* must be less than 3.

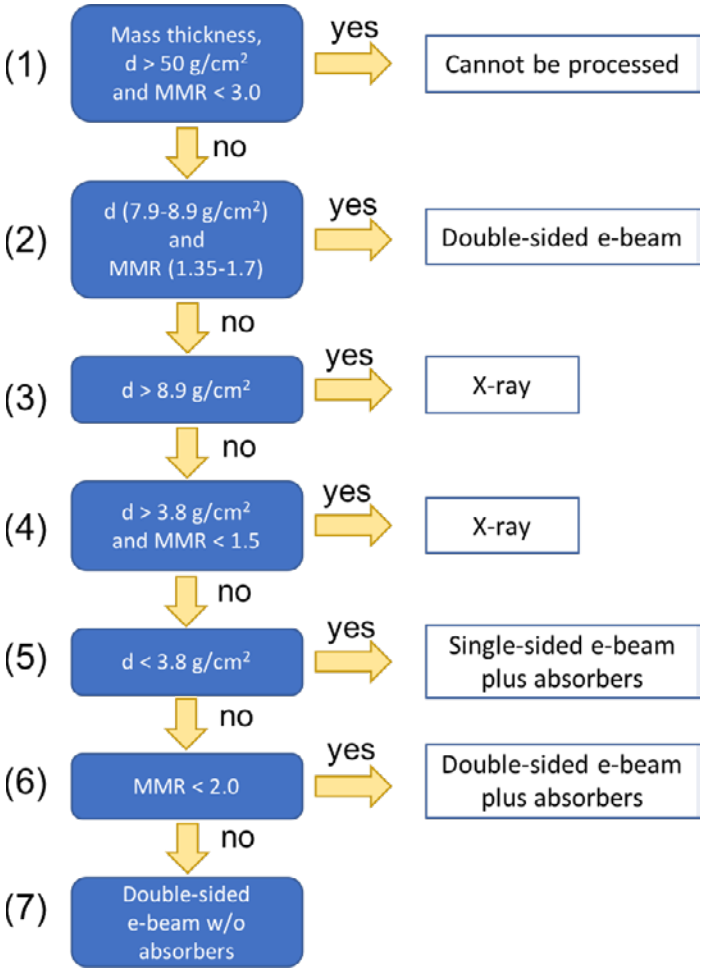

Figure 10. Decision flow diagram for selecting the correct irradiation approach (adapted from Miller, 2005). *MMR* is the acceptable range of maximum to minimum dose ratios (*DUR*).

Finally, the engineer must select the product handling systems to transport the food product in and out of the e-beam and X-rays irradiators via conveyors. Orientation of the irradiators is an important consideration since e-beams are oriented vertically to the product while the higher-penetrating X-rays allow for horizontal irradiation of products. The dose rate is set by varying the speed of the conveyors. The engineer must also determine whether absorbers must be used to reduce the entrance dose; provide refrigeration of the facility, if needed, since many food products are perishable; include shielding of the facility (X-rays require thicker walls than e-beam processing), and provide for ozone removal (a sub-product of irradiation from ionization of oxygen in the air) (Miller, 2005). Prior to entering the irradiation system, products are inspected in staging areas where products are palletized and loaded into containers to be transported on conveyers through the irradiators. Irradiated products are then loaded into transportation vehicles or stored in refrigerated chambers for distribution to retailers.

The speed, v, in cm/s, of the conveyor transporting the food through an e-beam scan facility is determined by (Miller, 2005):

$$v = \frac{1.85 \times 10^6 I_\mathrm{a}}{w D_\mathrm{sf}} \tag{13}$$

where I_a = average current (A), an e-beam accelerator configuration parameter

w = scan width (cm), an e-beam accelerator configuration parameter (see figure 11)

D_sf = the front surface dose (kGy), defined as the dose delivered at a depth d into the food (figure 11); the target dose

The conveyor speed is directly related to the throughput as:

$$v = \frac{dm/dt}{A_\mathrm{d} w} \tag{14}$$

where dm/dt = throughput or amount of product per time (g/s)

A_d = aerial density (g/cm^2) obtained from equation 15:

$$A_\mathrm{d} = \rho d \tag{15}$$

where ρ = food density (g/cm^3)

d = thickness (or depth) of food (cm)

Equations 13 and 14 show that for a system with fixed average current and scan width, the faster the speed of the conveyor, the more product is processed in the facility and the lower the dose it receives. Typical conveyor speeds range between 5 and 10 m/minute.

The total mass of product running through the conveyor belt is calculated as:

$$m = A_\mathrm{d} A_\mathrm{c} \tag{16}$$

where m = mass of food (kg)

A_d = aerial density from equation 15

A_c = cross-sectional area of food or package (m^2)

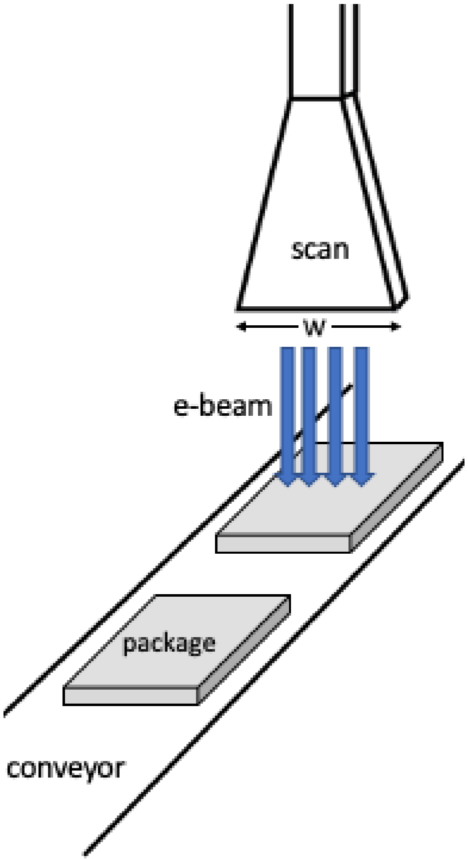

Figure 11. Typical electron beam irradiation configuration showing flat food packages placed onto the conveyor with the beam directed downward and scanned horizontally across the product. For double-beam irradiation a second beam is directed vertically upward (adapted from Miller, 2005).

The throughput requirements of electron beam facilities (*dm/dt*) are estimated based on the beam power, the minimum required dose, and irradiation mode (e.g., e-beam vs. X-rays) as follows (Miller, 2005):

$$\frac{dm}{dt}=\frac{\eta P}{D} \qquad \textbf{(17)}$$

where η = throughput efficiency, which is 0.025 to 0.035 at 5 MeV and 0.04 to 0.05 at 7.5 MeV for X-ray irradiation, and 0.4 to 0.5 for e-beam mode (Miller, 2005)
P = machine power (kW)
D = minimum dose requirement (kGy), which ranges from 250 Gy for disinfestation to 6–10 kGy for preservation of freshness for spices

Examples

Example 1: Interaction of ionizing radiation with matter

Problem:

If the incident current density at the surface is 10^{-6} A/cm^2 of the water absorber in figure 1 and the energy deposited per incident electron is 1.85 MeV-cm^2/g, determine the absorbed dose in kGy after 1 second.

Solution:

Using equation 6:

$$D(d)=E_{\mathrm{ab}}I_{\mathrm{A}}^{''}t \qquad \textbf{(6)}$$

$$D(d)=\left(1.85\ \mathrm{MeV}\frac{\mathrm{cm}^2}{\mathrm{g}}\right)\times\left(10^{-6}\ \frac{\mathrm{A}}{\mathrm{cm}^2}\right)\times 1\ \mathrm{s}$$

with 1 MeV = 10^6 eV:

$$D(d)=\left(1.85\times 10^{6}\ \mathrm{eV}\frac{\mathrm{cm}^2}{\mathrm{g}}\right)\times\left(10^{-6}\ \frac{\mathrm{A}}{\mathrm{cm}^2}\right)\times 1\ \mathrm{s}$$

In units of energy, 1 eV (electrovolt) equals 1.60218 × 10^{-19} Joules and 1 kJ = 1000 J

$$D(d)=\left(1.85\times 10^{6}\ \mathrm{eV}\frac{\mathrm{cm}^2}{\mathrm{g}}\right)\times\left(10^{-6}\ \frac{\mathrm{A}}{\mathrm{cm}^2}\right)\times 1\ \mathrm{s}\left(\frac{1\mathrm{C}}{1\ \mathrm{A}\times\mathrm{s}}\right)\times$$
$$\left(\frac{1.6022\times 10^{-19}\,\mathrm{J}}{1\ \mathrm{eV}}\right)\times\left(\frac{1}{1.6022\times 10^{-19}\,\mathrm{C}}\right)$$

Finally, the dose in kGy is:

$$D(d) = 1.85 \frac{\text{kJ}}{\text{kg}} \text{ or kGy}$$

The absorbed dose after 1 second is 1.85 kGy.

Example 2: Calculation of dose uniformity ratio (DUR)

Problem:

Figure 1 shows that the absorbed dose increases at a depth of 2.75 g/cm^2 inside the irradiated water absorber. (a) Find the dose uniformity ratio (*DUR*). (b) Comment on the changes (if any) to this parameter as a function of depth in the irradiated target.

Solution:

(a) Based on figure 1 and using equation 5, calculate the *DUR*:

$$DUR = D_{\text{max}}/D_{\text{min}} = 2.5/1.85 = 1.35$$

The *DUR* value is within the acceptable range for dose uniformity in commercial irradiator systems (close to 1.0).

(b) Based on figure 1, the *DUR* remains constant (= 1.35) up to a depth of 3.8 g/cm^2. Beyond this depth, the minimum dose decreases which increases the *DUR*. This is clearly shown in figure 1 as the dose increases with increasing depth within the product and then it decreases.

Example 3: Product thickness for one sided e-beam irradiation

Problem:

Determine the maximum allowable product thickness for one-sided e-beam irradiation with 10 MeV electrons if a dose uniformity ratio of 3 is acceptable.

Solution:

From figure 4 and using equation 5, determine the depth in cm for *DUR* = 3

$$DUR = D_{\text{max}}/D_{\text{min}}$$

D_{max} = 130% or 1.3 kGy (figure 4) and D_{min} = 1.3/3 = 0.43 kGy or 43% relative dose

Again, from figure 4, the depth value is 4.8 cm = r_{33}.

Thus, the maximum allowable product thickness will be 4.8 cm and the exit dose equals a third of the maximum dose.

Example 4: Efficiency of single-sided vs. double-sided irradiation treatment

Problem:

Determine the depth at the maximum throughput efficiency for single-sided and double-sided 10 MeV irradiation of water (5 cm thick) when the energy absorbed is (a) 1.50 MeV-cm^2/g, (b) 2.20 MeV-cm^2/g, and (c) 2.40 MeV-cm^2/g.

Solution:

Select the appropriate equation and calculate the depth in cm.

For single-sided irradiation use equation 7:

$$d_{\text{opt}} = 0.4 \times E - 0.2$$

(a) 1.50 MeV-cm^2/g

$$d_{\text{opt}} = 0.4 \times (1.50) - 0.2 = 0.40 \text{ g/cm}^2$$

(b) 2.22 MeV-cm^2/g

$$d_{\text{opt}} = 0.4 \times (2.22) - 0.2 = 0.68 \text{ g/cm}^2$$

(c) 2.40 MeV-cm^2/g

$$d_{\text{opt}} = 0.4 \times (2.40) - 0.2 = 0.76 \text{ g/cm}^2$$

For double-sided irradiation use equation 9:

$$d_{\text{opt}} = 0.9 \times E - 0.4$$

(a) 1.50 MeV-cm^2/g

$$d_{\text{opt}} = 0.9 \times (1.50) - 0.4 = 0.95 \text{ g/cm}^2$$

(b) 2.22 MeV-cm^2/g

$$d_{\text{opt}} = 0.9 \times (2.22) - 0.4 = 1.60 \text{ g/cm}^2$$

(c) 2.40 MeV-cm^2/g

$$d_{\text{opt}} = 0.9 \times (2.40) - 0.4 = 1.76 \text{ g/cm}^2$$

Energy Absorbed (MeV-cm^2/g)	d_{opt} (g/cm^2) Single-sided	d_{opt} (g/cm^2) Double-sided
1.50	0.40	0.95
2.22	0.68	1.60
2.40	0.76	1.76

Results demonstrate that the double-beam configuration is more effective regarding penetration depth with minimum energy utilization, e.g., penetration of 0.95 g/cm^2 versus 0.40 g/cm^2 using electron beams with 1.5 MeV-cm^2/g of energy.

Example 5: Interaction of ionizing radiation with food product and effect on dose penetration depth

Problem:

Comparisons of 10 MeV electron depth-dose distributions in a bag of vacuum-packed baby spinach leaves (mass thickness = 5.1 g/cm^2) and ground beef patty (mass thickness = 5.1 g/cm^2) are shown in figure 12. Determine the depth at which the maximum dose occurs for both food products and discuss your results.

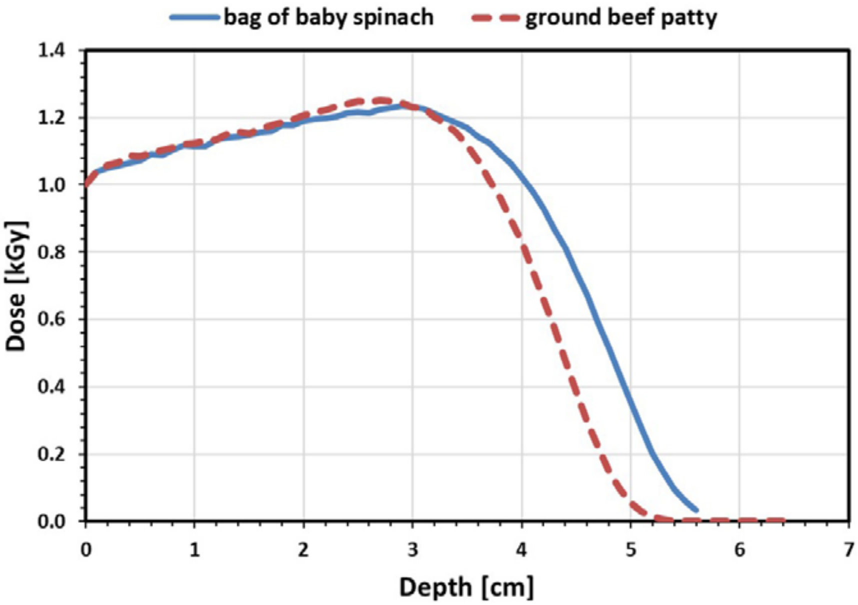

Figure 12. Absorbed dose vs. penetration depth in vacuum packed baby spinach leaves and ground beef patty at 10 MeV incident electron energy.

Solution:

Locate the depth (x-axis) at which dose (y-axis) is maximum. For the spinach, depth is 3.00 cm and for the ground beef patty, depth = 2.70 cm.

Both materials have very similar atomic composition and, therefore, absorb the incident energy very similarly.

Example 6: Calculation of radiation D_{10} value

Problem:

Romaine lettuce leaves were exposed to radiation doses up to 1.0 kGy using a 10 MeV e-beam irradiator to inactivate a pathogen. The population of survivors at each dose was measured right after irradiation (see table below).

Number of pathogens (CFU/g) in romaine lettuce leaves as a function of radiation dose:

Dose (kGy)	Population (log CFU/g)
0	6.70
0.25	5.50
0.50	4.30
0.75	3.30
1.00	2.00

(a) Calculate the D_{10} value of the pathogen in the fresh produce and determine the dose level required for a 5-log reduction in the population of the pathogen. The data point for a dose of 0 kGy represents the non-irradiated produce.

(b) If the maximum dose approved for irradiation of fresh vegetables is close to 1 kGy, is the irradiation treatment suitable?

Solution:

First, plot the logarithm of the population of survivors as a function of dose from the given data and determine the D_{10} value from the inverse of the slope of the line (figure 13).

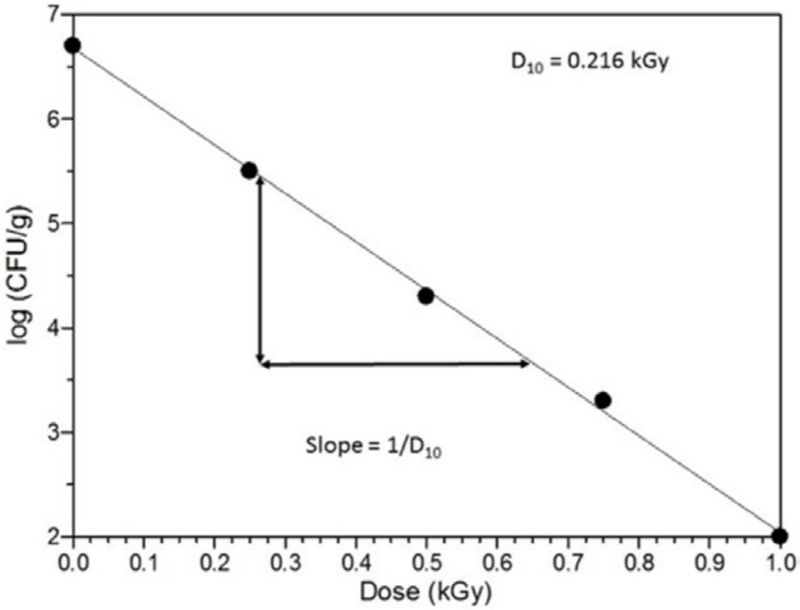

Figure 13. D_{10} value calculation assuming radiation inactivation as 1st order kinetics.

$$\text{Slope} = -\frac{\log N_1 - \log N_2}{D_1 - D_2} = -\frac{5-4}{0.375-0.591} = -\frac{1}{-0.216} = \frac{1}{0.216}$$

Then, determine the dose required for a 5-log reduction in microbial population, i.e., $5D_{10}$, and check if $5D_{10} < 1.0$ kGy. If yes, the process is suitable for treatment of the fresh produce. If $5D_{10} > 1.0$ kGy, another process should be considered.

$$5D_{10} = 5 \times 0.216 \text{ kGy} = 1.10 \text{ kGy}$$

This irradiation process would be suitable because the pathogen population in the romaine lettuce leaves will be reduced by 5 logs when exposed to a dose of approximately 1.0 kGy using 10 MeV electron beams.

Example 7: Selection of best irradiation technology

Problem:

A 10 MeV e-beam and a 5 MeV X-ray accelerator are available for irradiating the following products. Select the best irradiation technology to treat each of the products. Assume a minimum dose of 1 kGy.

(a) Ground beef patty contaminated with *Escherichia coli* O157:H7, $D_{max} = 1.25$ kGy (mass thickness = 8.5 g/cm^2)
(b) Tomato contaminated with *Listeria monocytogenes*, $D_{max} = 1.4$ kGy (mass thickness = 3.2 g/cm^2)
(c) Romaine lettuce contaminated with *Salmonella* Poona, $D_{max} = 1.37$ kGy (mass thickness = 4.1 g/cm^2)

Solution:

Use the given information and the flow chart (figure 10) to determine whether e-beams or X-rays should be used for irradiation of the different products.

(a) *DUR* for beef patty (using equation 5, $DUR = D_{max}/D_{min}$) = 1.25 kGy/1 kGy = 1.25 = *MMR*

Following figure 10 with mass thickness $d = 8.5$ g/cm^2 and $MMR = 1.25$ leads to condition 4: $d > 3.8$ g/cm^2 and $MMR < 1.5$ and selection of X-ray as the appropriate technology for the beef patty.

(b) *DUR* for tomato sample (using equation 5, $DUR = D_{max}/D_{min}$): 1.4 kGy/1 kGy = 1.4 = *MMR*

Following figure 10 with mass thickness $d = 3.2$ g/cm^2 and $MMR = 1.4$ leads to condition 6 or 7: $d < 3.8$ g/cm^2 and selection of single or double-sided e-beam would be appropriate for the tomato sample.

(c) *DUR* for romaine lettuce (using equation 5, $DUR = D_{max}/D_{min}$): 1.37 kGY/1 kGy = 1.37 = *MMR*

Following figure 10 with mass thickness $d = 4.1\ \text{g/cm}^2$ and $MMR = 1.37$ leads to condition 4: Mass thickness $d = 4.1\ \text{g/cm}^2$. Since $d > 3.8\ \text{g/cm}^2$ and $MMR < 1.5$, select X-ray as the appropriate technology for the romaine lettuce.

Product	Criteria	Choice of Radiation Technology
Beef patty	$d > 3.8\ \text{g/cm}^2$, $MMR < 1.5$	X-rays
Tomato	$d < 3.8\ \text{g/cm}^2$, $MMR < 1.5$	E-beams
Romaine lettuce	$d > 3.8\ \text{g/cm}^2$, $MMR < 1.5$	X-rays

Example 8: Calculate the dose required for a 5-log reduction of pathogen population

Problem:

Calculate the dose required for a 5-log reduction of the pathogen for the three products from Example 7 using the following information. For each product, determine if the required dose is less than the maximum allowable dose for that product.

(a) Ground beef patty contaminated with *Escherichia coli O157:H7* ($D_{10} = 0.58$ kGy)
(b) Tomato contaminated with *Listeria monocytogenes* ($D_{10} = 0.22$ kGy)
(c) Romaine lettuce contaminated with *Salmonella* Poona ($D_{10} = 0.32$ kGy)

Solution:

Given the D_{10} value for each pathogen, calculate 5D. The pathogen with the higher 5D value is the more resistant to irradiation and will require treatment at higher doses.

Product	Pathogen	5D (kGy)
Ground beef patty	*Escherichia coli* O157:H7	2.90
Tomato	*Listeria monocytogenes*	1.10
Romaine lettuce	*Salmonella* Poona	1.60

The *E. coli* in the beef patties will require higher doses to achieve a 5-log inactivation level than the doses required to treat the two fresh produces. The required treatment for the tomato samples falls within the acceptable dose level for fruits and vegetables (about 1 kGy). The *Salmonella* in the lettuce will require a slightly higher dose but the U.S. Food and Drug Administration (FDA, 2018) allows up to 4 kGy for treatment of leafy greens. The maximum allowable dose for pathogen inactivation in fresh and frozen beef ranges from 4.5–7.0 kGy in different countries (table 4).

Example 9: Calculation of conveyor speed in an e-beam system

Problem:

Calculate the conveyor speed required for a 1.5 kGy entrance dose (front surface dose) irradiation for a single-sided process using a 10 MeV, 1-mA beam with a scan width of 120 cm.

Solution:

Calculate the conveyor speed using equation 13:

$$v = \frac{1.85 \times 10^6 I_\mathrm{a}}{w D_\mathrm{sf}}$$

The conveyor speed, v, with the given values of D_sf = 1.5 kGy, $I_\mathrm{a} = 10^{-3}$ A and w = 120 cm is:

$$v = \frac{1.85 \times 10^6 I_\mathrm{a}}{w D_\mathrm{sf}} = \frac{1.85 \times 10^6 \times 10^{-3}}{120 \times 1.5} = 10.28 \text{ cm / s}$$

Conveyor speed varies according to product throughput. In this case, the conveyor must run at 10.28 cm/s (6 m/min) to ensure a 1.5 kGy entrance dose when treating the food with a 10 MeV e-beam accelerator in singled-sided mode and given current and scan width. The faster the conveyor speed, the lower the dose. For instance, if the required D_sf is 1 kGy, then the conveyor should run at 15.42 cm/s (9.25 m/min):

$$v = \frac{1.85 \times 10^6 I_\mathrm{a}}{w D_\mathrm{sf}} = \frac{1.85 \times 10^6 \times 10^{-3}}{120 \times 1} = 15.42 \text{ cm / s}$$

Example 10: Calculation of throughput rate for an e-beam system

Problem:

Calculate the throughput rate for e-beam disinfestation of papaya (minimum required dose of 0.26 kGy) with an e-beam irradiation (one-sided mode) with 12 kW of power and throughput efficiency of 0.5.

Solution:

(a) Calculate the throughput rate with P = 12 kW, D = 0.26 kGy, and η = 0.5.
From equation 17:

$$\frac{dm}{dt} = \frac{\eta P}{D}$$

Then:

$$\frac{dm}{dt}\left[\frac{\text{kg}}{\text{s}}\right] = \frac{0.5 \times 12[\text{kW}]}{0.26[\text{kGy}]} = 23.1 \text{ kg / s}$$

(b) Assuming an areal density of 7 g/cm² and a scan width of 120 cm, calculate the conveyor speed, *v*.

Find *v* using equation 14:

$$v = \frac{dm/dt}{A_\mathrm{d} w}$$

with $A_\mathrm{d} = 7\ \mathrm{g/cm^2}$, then:

$$v = \frac{dm/dt}{A_\mathrm{d} \times w} = \frac{23.1\left[\frac{\mathrm{kg}}{\mathrm{s}}\right] \times 1000\left[\frac{\mathrm{kg}}{\mathrm{g}}\right]}{7\left[\frac{\mathrm{g}}{\mathrm{cm}^2}\right] \times 120[\mathrm{cm}]} = 27.5\ \mathrm{cm/s}$$

(c) If the product is arranged in cardboard boxes (figure 11), which have a cross sectional area of 7432 cm², calculate the total mass of food that should be placed in a box

Find *m* using equation 16:

$$m = A_\mathrm{d} A_\mathrm{c}$$

with $A_\mathrm{d} = 7\ \mathrm{g/cm^2}$ and $A_\mathrm{c} = 7432\ \mathrm{cm^2}$, then:

$$m = A_\mathrm{d} \times A_\mathrm{c} = \frac{7\left[\frac{\mathrm{g}}{\mathrm{cm}^2}\right] \times 7432\left[\mathrm{cm}^2\right]}{1000\left[\frac{\mathrm{g}}{\mathrm{kg}}\right]} = 52\ \mathrm{kg}$$

Disinfestation treatment of papaya (dose of 0.26 kGy) using a one-sided e-beam can be achieved when 52 kg of the food is placed under the e-beam with the conveyor running at 27.5 cm/s.

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Example 5. Moreira, R. G. (CC By 4.0). (2020). Example 5.

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