About Our Cover

Irradiation of Horticultural Crops at Iowa State University

BASIC CHARACTERISTICS OF IRRADIATION AND IRRADIATION FACILITIES

Overview

For millennia, people have searched for methods for safely preserving perishable products. Curing, low-temperature storage, canning, freezing, pasteurization, and dehydration are conventional forms of preservation that have been used successfully. Ionizing radiation also can be used for the long-term preservation of various perishable products. For food products, the use of ionizing radiation has distinct advantages over some of these conventional forms of preservation. One advantage is that irradiation can be done after the product has been packaged, and this reduces opportunities for postprocessing contamination. A second advantage is that there are no residues after irradiation. Irradiation processing of foods and other products has been approved in more than 38 countries, and commercial food irradiation is occurring in 30 pilot plants and commercial plants in 25 countries. In the United States, however, there is only one dedicated commercial food irradiation facility; therefore, most irradiation of foods and other products occurs outside the United States. In the United States, four retail stores have marketed irradiated products, such as strawberries (*Fragaria × ananassa* Duch.), for more than 4 years, and they have been accepted by consumers.

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Front cover: The front cover and Figs. 2 and 3 of the cover story were photographed by Peter Krumhardt, a freelance photographer from central Iowa. Items on the front cover either are approved for irradiation or they are the subject of current irradiation research. The roses in Fig. 3 were donated by Greenleaf Wholesale Florists, Inc., Des Moines, Iowa. (See related story on electron-beam irradiation on p. 698 of this issue.)

Types of ionizing radiation

Gamma-ray and X-ray radiation have short wavelengths; therefore, they contain more energy per photon than radiation of longer wavelengths. Photons of gamma rays or X-rays have several million electron volts (MeV) of energy. Gamma rays are produced during the disintegration of certain radioactive isotopes, such as cobalt-60 (⁶⁰Co) and cesium-137 (¹³⁷Cs), and gamma rays typically contain photons with energy levels of ≈1 MeV. Electrons in an unaccelerated state are in a relatively low energy level, but they can be accelerated to energy levels of up to 10 MeV by using a linear accelerator or a Van de Graff generator. Accelerated electrons can be used directly to irradiate materials such as foods, ornamental crops, and other products. Accelerated electrons also can be converted to X-rays by directing the electrons to collide with a heavy metal target such as tungsten. Bremsstrahlung X-rays are emitted as a result of this collision, and these X-rays can be used for irradiation. However, the conversion rate of high-energy electrons into X-rays is very low, which makes use of bremsstrahlung X-

rays too inefficient for commercial use with current technology.

Irradiation dose

The key factor in irradiation is the dose, which is the amount of radiation energy absorbed by the product. The unit of measure of radiation dose in the International System of Units is the Gray (Gy), and 1 Gy is equal to the absorption of 1 J of energy per kilogram of product irradiated. Radiation doses are divided into three broad doses: high (>10 kGy), medium (1 to 10 kGy), and low (<1 kGy). At high doses, the product is sterilized. At medium doses, there is a "pasteurization" effect that leads to extended shelf life due to either total destruction of or a reduction in the number of most pathogenic and spoilage microorganisms. At low doses, the product is disinfested from insects and other higher life forms, the ripening of fruits and vegetables may be delayed, sprouting of potatoes and onions is inhibited, and various physiological processes may be altered. In almost all cases, the dose that a product receives is controlled by the time of exposure to a given type of radiation (e.g., gamma rays, X-rays, or a beam of high-energy electrons).

Basic components of an irradiation facility

All irradiation facilities have some common characteristics. These include a radiation

Fig. 1. The radura seal signifies that the product has been treated with radiation. This seal, which is green when used commercially, must accompany the presentation of all irradiated items in all parts of the world.

Fig. 2. Machine for generating and accelerating electrons. Component parts of the machine are: (A) Klystron tube; (B) electron gun; (C) accelerating chamber with magnets for accelerating electrons; (D) apparatus for bending path of electrons 107°; (E) scanning magnet that sweeps the electrons across the product; (F) opening through floor into irradiation chamber on floor below.

Fig. 3. Irradiation chamber. Component parts of the irradiation chamber are: (A) opening in ceiling for horn that distributes electrons; (B) horn through which electrons travel to shower the target to be irradiated; (C) concrete walls that total 3 m in thickness; (D) cart that carries products to be irradiated; (E) conveyor system for transporting carts into and out of maze in the irradiation chamber; (F) specially designed holder for rose irradiation; (G) roses as the irradiation target.

source, a biological shield, a transport system for product handling, an air evacuation system, and a safety and control system.

Crops approved for irradiation

In the United States, approval is sought by petitioning the Food and Drug Administration (FDA). The petition must include evidence of scientific studies that substantiate the safety and wholesomeness of the irradiation process for a particular product. Approvals for the use of irradiation technology have been granted to various degrees in many countries. In the United States, approvals exist for disinfesting any fruit or vegetable by irradiating at dosages of <1 kGy. In addition, the FDA has granted approval for the irradiation sterilization of dried spices and dehydrated vegetable seasonings at doses up to 30 kGy. Throughout the world, irradiated products must bear the radura seal (Fig. 1), which signifies the treatment. The radura seal was developed in The Netherlands, must be green when associated with an irradiated product, and is recognized internationally. In the United States, the product label also must state that the product has been treated with ionizing radiation or by irradiation.

THE LINEAR ACCELERATOR FACILITY AT IOWA STATE UNIVERSITY

General characteristics

The linear accelerator facility at Iowa State University is designed to irradiate foodstuffs and other materials. High-energy electrons are produced and accelerated in a commercially available machine (Fig. 2), and the product receives its radiation treatment in the irradiation chamber located one floor below the accelerator (Fig. 3). The facility takes up 650 m² (7000 ft²), and the irradiation chamber is 14 m² (150 ft²). Construction of the facility took 2 years, and the cost was about \$6,000,000. Funding came from grants to Iowa State Univ. from the U.S. Dept. of Energy and the State of Iowa. We will discuss the basic components of the linear accelerator facility at Iowa State Univ. These components are common parts of many, but not all, irradiation facilities throughout the world. The components are the biological shield, the transport system for product handling, the air evacuation system, the safety and control system, and irradiation sources and types. Finally, we will present a comparison of the facilities necessary for irradiation with either electrons or X-rays. Cooperative research efforts with other universities and government laboratories are solicited and desired. Research efforts may include studies on enhanced food safety, extended shelf life, combination processes for shelf-stable products, packaging materials and methods, and consumer acceptance.

Biological shield

The irradiation process area (chamber) in the Iowa State facility is surrounded by thick

concrete walls (≈ 3 m), including the floor and ceiling. These walls serve as a shield so that X-rays cannot penetrate through the walls, floor, or ceiling to expose people, or other biological organisms, to irradiation. Other materials such as lead can be used as this shield, but concrete is more economical. The thickness of this biological shield depends on the energy of the irradiation source. Concrete 2 m thick is needed to shield gamma rays from a ^{60}Co source (1 to 2 MeV), whereas concrete 3 m thick is needed to shield a 10-MeV source that uses accelerated electrons or produces X-rays. The biological shield can be several walls that together constitute the required thickness.

Transport system and product handling

The transport system is a critical component of the irradiation facility. Conveyor speed is the primary method for controlling the dose the product receives and must be adjusted to account for changes in the dose rate. In the Iowa State electron-beam facility, the machine that generates the electrons can have a variable power level that changes the amount of electrons generated and, therefore, the dose rate. Items are exposed to the irradiation source in a continuous process, and the products are moved by a transport system through a maze that has at least three right-angle turns so that gamma rays and X-rays cannot ricochet off walls and escape the biological shield. In the Iowa State electron-beam facility, the products are placed on a conveyor supported from the floor, and the electrons are scanned across the product from above. The actual time of exposure of the product to a beam of electrons often is measured in seconds and rarely lasts more than a few minutes. The conveyor loading area is separated by a fence from the unloading area, to prevent co-mingling of irradiated and nonirradiated products. Labeling and dosimetry are important in preventing nonirradiated products from being confused with irradiated products. At commercial facilities, docks for unloading trucks of products to be irradiated usually are separated from docks used to load trucks with irradiated products.

Air evacuation system

Ozone, a by-product of the irradiation process, forms when gamma rays or electrons ionize oxygen in the air. The ionized oxygen subsequently combines to form ozone. Ozone must be removed from the irradiation chamber and the product handling area before people are exposed to it. Ozone is removed by an air evacuation system that draws outside air into the irradiation chamber and exhausts that air to the outside. To comply with environmental regulations, a large volume of air is needed to dilute the ozone to permissible levels. The large volume of air used for ozone dilution makes it economically impractical to refrigerate the irradiation chamber. Hence, consideration of the time a refrigerated product resides in the irradiation chamber is important. Monitoring and recording product temperature be-

fore and after irradiation are required in many inspection protocols for various products. Elevated temperatures in some regions may cause concern for temperature abuse of refrigerated products that reside in an irradiation chamber for an extended period. Under normal circumstances, however, the actual event of low-dose irradiation increases product temperature by only $\approx 1^\circ\text{C}$ when it is at room temperature at the start of irradiation.

Safety and control system

Safety systems are designed to prevent the accidental exposure of people to radiation. Although an absolutely fail-safe system can never be developed, several monitoring and warning devices can ensure very safe operating conditions that prevent accidental exposure. These devices include sensors, detectors, warning lights, and alarms. When not in operation, the irradiation source, a high-voltage system in an electron-beam facility, is placed in a safety mode so that people in the irradiation process area will not be exposed to irradiation. The conveyor systems are designed so that a person cannot ride into the irradiation chamber on the conveyor or enter the irradiation chamber maze in front of or behind the product carriers on the conveyor. Intrusion of the irradiation chamber maze is detected by electronic sensors on the access door, pressure mats on the floor, and light curtains. Activation of any of these sensors or detectors returns the irradiation source to a safe mode in which no electrons are generated and accelerated.

Irradiation source and types

At Iowa State Univ., the irradiation source is an electron-beam accelerator that generates and accelerates electrons under vacuum. Several types of electron-beam accelerators are used for industrial applications. For food irradiation, radio frequency linear accelerators are used. They produce electrons with energies of 5 to 10 MeV and maximum power from 10 to 50 kW. Because the power of electron-beam accelerators is high, products are moved under the electron beam rapidly, and the appropriate dosage is applied rapidly. The rapid conveyor speed of an electron beam facility exposes chilled products to ambient temperatures only briefly; therefore, it is unlikely that the products will have an unacceptable increase in temperature. Because of their small mass, electrons cannot penetrate deeply into a product, but higher energy electrons have greater penetration into the product. The maximum energy approved for use in food is 10 MeV. At energy levels of 5 and 10 MeV and with irradiating from both sides of a product, the maximum thickness of an irradiated product is 3.75 and 7.50 cm, respectively. Hence, accelerated electrons cannot be applied to all types of products, such as pallet loads, because they are too thick. Thus, electron-beam irradiation probably will be used as a part of a manufacturing line, and the products will be irradiated in a single layer before they are boxed and palletized. To overcome the limita-

tion of product thickness when accelerated electrons are used for irradiation, electrons can be directed at a heavy metal target, such as tungsten, to produce bremsstrahlung X-rays. These X-rays are similar in energy level to gamma rays and can penetrate thick products. However, the yield of bremsstrahlung X-rays from an electron source is low, and the efficiency of the process is $<8\%$.

Comparison of facilities

Gamma-ray and electron-beam facilities have many common characteristics because both result in ionizing radiation. However, the radiation sources cause differences in safety and malfunction procedures, maintenance procedures, product configuration, and operations. The most critical difference is that the ^{60}Co source of gamma rays can never be turned off. The source must be transported, loaded into the facility, and always be handled with a biological shield to protect workers from exposure. In addition, the ^{60}Co source is stored in tanks of water when not in use. However, there is a long history of safe use and handling of ^{60}Co in medical device sterilization facilities. There also is the possibility that a ^{60}Co pencil (a long, thin rod that contains the radioactive source) could become defective and some of the ^{60}Co could escape from the pencil. Because ^{60}Co is not soluble in water, the released material can be isolated and vacuumed out of the water pool. There is continuous decay of ^{60}Co , and the number of curies, a measure of radioactivity, in the source is decreasing constantly. Therefore, the source must be replenished (often annually) to maintain the desired efficiency in the facility. In an electron-beam facility, electricity is the source that generates electrons. Therefore, there is no inherent radioactivity in the facility, and the instrument can be transported and installed without a biological shield. Malfunctions trip electrical relays to the high-voltage source, and electron generation stops immediately. Electron-beam instruments have many systems (electrical, water, and vacuum) that potentially could fail and result in a loss of operations. Considerably more maintenance is required in the various systems of a linear accelerator facility than is needed for a corresponding gamma facility. Also, some components, such as the modulator and the electron and radio-frequency generators, have a finite, useful life. There likely will be more service interruptions with an electron-beam facility than with a gamma facility.

IRRADIATION OF HORTICULTURAL CROPS AT IOWA STATE UNIVERSITY

Strawberries

Fresh 'Tristar' strawberries were treated with electron-beam irradiation doses of 0, 0.5, 1, and 2 kGy at 10 MeV. The intensity of the redness and objectively measured firmness decreased as the dosage increased, and panelists rated irradiated fruit less firm than

nonirradiated fruit stored for 1, 2, or 4 days. Irradiation suppressed fungal growth (mainly *Botrytis cinerea* Pers.) on stored berries, and irradiation doses of 1 and 2 kGy extended berry shelf life by 2 and 4 days, respectively. Thus, electron-beam irradiation has excellent potential for extending the shelf life of fresh strawberry fruits by suppressing fungal growth (Yu et al., 1995). Additionally, water-soluble pectin content increased and oxalate-soluble pectin content decreased 0 and 1 day after irradiation doses of 1 and 2 kGy. Decreasing oxalate-soluble pectin concentration and fruit firmness were correlated. Total pectin and nonextractable pectin concentrations were not affected by irradiation dosage. Oxalate-soluble pectin concentration and firmness increased slightly at the beginning of the storage period at 2 °C, but they subsequently decreased as storage time increased. No changes were found in water-soluble, nonextractable, or total pectin during 8 days of storage (Yu et al., 1996).

Roses

Cut *Rosa ×hybrida* L. 'Royalty' flowers received doses of 0 to 4 kGy of electron-beam irradiation at 10 MeV and a dose rate of 45

kGy·min⁻¹. Doses of 0.25 and 0.50 kGy slowed the rate of flower opening without decreasing flower quality, but ≥0.75 kGy decreased flower quality ratings to levels that were unacceptable. Inoculated and natural populations of *Botrytis cinerea* were not controlled by irradiation doses that did not cause a loss of flower quality. Thus, electron-beam irradiation of roses cannot be used to eradicate or reduce fungal populations without decreasing flower quality. Conidia population decreased substantially only when irradiation doses exceeded 2 kGy, and this dosage was damaging to petal tissue (Chang et al., 1997).

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