Problems with fresh produce

- Recent cases of foodborne disease outbreaks associated with fresh vegetables have influenced consumer perception about the safety of the food supply
Spinach – source of contamination

- The ‘bad seed’ episode from CSI Miami
Ground Beef

- States with Outbreak-Associated Cases of *E. coli* O157, October 2007

[Map showing states in green]
Spinach, Oct. 2006

E. coli O157:H7 Outbreak Case Counts by State

CDC
Fresh cut vegetables

Salmonella Wandsworth Outbreak, June 2007
Major factors causing foodborne disease

- Fresh produce do not receive a lethality step to inactivate pathogens during processing.
- The growth potential of these microorganisms under current produce storage practices.
Problem is even greater

- Potential internalization of pathogenic organisms into the core of fruits and vegetables
- Surface treatments to reduce pathogens very ineffective
- Need for alternative pasteurization or decontamination practices
Food irradiation is a technology for controlling spoilage and eliminating foodborne pathogens. Often called "cold pasteurization" or "irradiation pasteurization." The FDA emphasizes that no preservation method is a substitute for safe food handling procedures.
Quantity of irradiated foods in the world in 2005 was 405,000 ton.

Commercial food irradiation is increasing significantly in Asia, but decreasing in EU.
Microbiological effect
How food is irradiated?

- Bulk or packaged food passes through a radiation chamber on a conveyor belt.
- The food does not come into contact with radioactive materials, but instead passes through a radiation beam, like a large flashlight.
- The type of food and the specific purpose of the irradiation determine the amount of radiation, or dose, necessary to process a particular product.
- The speed of the belt helps control the radiation dose delivered to the food by controlling the exposure time.
- The actual dose is measured by dosimeters within the food containers.
Sources

- The food irradiation process uses three types of ionizing radiation sources:
  - cobalt-60 gamma sources
  - electron beam generators
  - x-ray generators
Co-60

- The radionuclide used almost exclusively for the irradiation of food by gamma rays.
- It is produced by neutron bombardment in a nuclear reactor of the metal Co-59, then doubly encapsulated in stainless steel “pencils” to prevent any leakage during its use in a radiation plant.
- Cobalt-60 has a half-life of 5.3 years.
- Emits ionizing radiation in the form of intense gamma rays.
- "Gamma facilities" store it in stainless steel capsules (like "pencils" of cobalt), in underwater tanks.
To create its C-188 sources, MDS Nordion welds nickel-plated inactive cobalt-59 slugs into Zircaloy capsules. These capsules are assembled into reactor targets and installed in reactors. Typically, within 18 to 24 months, the targets achieve the desired cobalt-60 specific activity. They are then removed, disassembled and shipped. Trained staff double-encapsulate the cobalt-60 into C-188 sources.
Co-60

- **Cobalt-60 advantages:**
  - up to 95% of its emitted energy is available for use
  - penetrates deeply
  - yields substantial uniformity of the dose in the food product
  - decays to non-radioactive nickel
  - considered to pose low risk to the environment.

- **Cobalt-60 disadvantages:**
  - 5.3-year half-life
  - cobalt-60 "pencils" require frequent replenishment
  - treatment of the food is relatively slow.
Co-60 facility
Cesium-137

- Cesium-137 is a gamma source that is also used for irradiation.

- Characteristics:
  - Less penetrating gamma beam
  - A longer half-life, making it more suitable under certain circumstances
Electron-beam accelerators

- Electron beam facilities generate e-beams with an electron beam linear accelerator.
- It works on the same principle as a television tube.
- The electrons are concentrated and accelerated to 99% of the speed of light and energies of up to 10 MeV.
E-beam accelerators

- Because e-beams are generated electrically, they offer certain advantages:
  - they can be turned on only as needed
  - they do not require replenishment of the source as does cobalt-60
  - there is no radioactive waste

- E-beam technology also has disadvantages
  - shallow depth of penetration
  - e-beams must be converted to x-rays to penetrate large items such as carcasses
  - high electric power consumption
  - complexity, and potentially high maintenance
## Food Irradiation Technologies

<table>
<thead>
<tr>
<th></th>
<th>E-beam</th>
<th>X-ray</th>
<th>Co-60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [MeV]</td>
<td>10</td>
<td>5 or 7</td>
<td>1.17 and 1.33</td>
</tr>
<tr>
<td>Penetration [cm]</td>
<td>&lt; 10</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>Irradiation on demand</td>
<td>Power stop</td>
<td>Power stop</td>
<td>Not possible</td>
</tr>
<tr>
<td>Throughput</td>
<td>+++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Dose uniformity [Dmax/Dmin]</td>
<td>+</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Treatment time</td>
<td>seconds</td>
<td>minutes</td>
<td>hours</td>
</tr>
<tr>
<td>Dose rate</td>
<td>Very high</td>
<td>medium</td>
<td>low</td>
</tr>
</tbody>
</table>
Electron-beam Facility – 5 MeV
X-rays Facility
X-ray facilities

- Use an electron beam accelerator to target electrons on a metal plate.
- Although some energy is absorbed, the rest is converted to X-rays.
- Like gamma rays, X-rays are penetrating, and can be used on food boxes 15 inches thick or more.
- This allows food to be processed in a shipping container.
- X-rays offer the advantage of high penetration, but share the other e-beam technology disadvantages.
# IBA e-beam specifications

<table>
<thead>
<tr>
<th></th>
<th>Electron Energy</th>
<th>Beam Current</th>
<th>Throughput*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shallow Penetration E-Beam</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALIS</td>
<td>100 to 200 keV</td>
<td>0 - 3.5 mA</td>
<td>Up to 5 tubs/minute</td>
</tr>
<tr>
<td><strong>Medium Penetration E-Beam</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamitron®</td>
<td>300 keV to 5 MeV</td>
<td>0 - 160 mA</td>
<td></td>
</tr>
<tr>
<td>Self Shielded Easy-e-Beam</td>
<td>300 keV to 1.5 MeV</td>
<td>0 - 100 mA</td>
<td>Application dependent</td>
</tr>
<tr>
<td>Self Shielded RF E-Beam</td>
<td>2 to 5 MeV</td>
<td>0.5 to 2 mA</td>
<td></td>
</tr>
<tr>
<td><strong>Deep Penetration E-Beam</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhodotron® TT100</td>
<td>3 to 10 MeV**</td>
<td>0 - 3.5 mA</td>
<td>Up to 80,000 m³/year*</td>
</tr>
<tr>
<td>Rhodotron® TT200</td>
<td>3 to 10 MeV**</td>
<td>0 - 8 mA</td>
<td>Up to 150,000 m³/year*</td>
</tr>
<tr>
<td>Rhodotron® TT300</td>
<td>3 to 10 MeV**</td>
<td>0 - 19 mA</td>
<td>Up to 250,000 m³/year*</td>
</tr>
<tr>
<td><strong>X-Ray Pallet Irradiation System</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX200</td>
<td>5 or 7 MeV</td>
<td>0 - 15 mA</td>
<td>Up to 20,000 m³/year*</td>
</tr>
<tr>
<td>TX400</td>
<td>5 or 7 MeV</td>
<td>0 - 40 mA</td>
<td>Up to 60,000 m³/year*</td>
</tr>
<tr>
<td>TX1000</td>
<td>5 or 7 MeV</td>
<td>0 - 100 mA</td>
<td>Up to 150,000 m³/year*</td>
</tr>
</tbody>
</table>
Dynamitron – e-beam
Energy

- When materials are irradiated using a one-sided penetration approach, the part of the e-beam that penetrates beyond the equal-entrance-exit depth is essentially wasted.

- So, by irradiating from two opposite sides, you not only recover that energy, but can handle thicknesses much greater than before.
Beam delivery for LINAC

- Double beam
- Top and bottom sources at specific conveyor speed
Cantaloupe irradiated using 10MeV e-beam - lower beam direction

Dosimeters location  CT scan image  Monte Carlo simulation
10 MeV e-beam - 1 kGy
Material Thickness

- Calculating the way an e-beam distributes absorbed energy in a material results in a very different plot than the familiar attenuation curves of gamma rays or X-rays.
- The energy deposited by an electron, the dose, actually increases at first as the beam penetrates the material.
- After reaching its highest level within the material, the dose decreases to zero based upon the amount of energy applied and the composition of the material.
Rhodotron- X-ray
Absorbed Dose

RADIATION DOSE EQUIVALENTS

Standard
International = gray = 1 joule/kilogram
Unit

Traditional = rad = 100 ergs/gram
Unit

Most applications require doses in the kilogram (or megarad) range

Equivalents
1 gray = 100 rads
1 kilogram = 0.1 megarad
10 kilogram = 1 megarad
Radiation dose to the food

- Radiation doses vary for different foodstuffs.
- For the vast majority of foods, the limit is less than 10 kGy.
- The U.S. Food and Drug Administration (FDA) sets radiation dose limits for specific food types:

<table>
<thead>
<tr>
<th>Food Type</th>
<th>Dose (kiloGrays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fruit</td>
<td>1</td>
</tr>
<tr>
<td>poultry</td>
<td>3</td>
</tr>
<tr>
<td>spices, seasonings</td>
<td>30</td>
</tr>
</tbody>
</table>
How does irradiation kill bacteria?

- When ionizing radiation strikes bacteria and other microbes, its high energy breaks chemical bonds in molecules that are vital for cell growth and integrity.
- As a result, the microbes die, or can no longer multiply, causing illness or spoilage.
- Breaking chemical bonds with radiation is known as radiolysis.
Effects of Irradiation

- Direct effect
  - single and double strand break of DNA
- Indirect effect
  - radiolysis of water
  - formation of OH radicals
Variations in $D_{10}$ values (in kGy) for *Escherichia coli*

<table>
<thead>
<tr>
<th>Strain</th>
<th>Substrate</th>
<th>$D_{10}$</th>
<th>Temp. [°C]</th>
<th>Irradiation Source</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>B/r</td>
<td>66.7mM Pi</td>
<td>0.011</td>
<td>2</td>
<td>X-ray</td>
<td>Hollaender et al (1951)</td>
</tr>
<tr>
<td>B/r</td>
<td>66.7mM Pi</td>
<td>0.012</td>
<td>2</td>
<td>X-ray</td>
<td>Hollaender et al (1951)</td>
</tr>
<tr>
<td>B/r</td>
<td>66.7mM Pi</td>
<td>0.32</td>
<td>2</td>
<td>X-ray</td>
<td>Hollaender et al (1951)</td>
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<tr>
<td>B/r</td>
<td>66.7mM Pi</td>
<td>0.36</td>
<td>2</td>
<td>X-ray</td>
<td>Hollaender et al (1951)</td>
</tr>
<tr>
<td>B/r</td>
<td>Saline-Pi</td>
<td>0.09</td>
<td>-</td>
<td>X-ray</td>
<td>Hollaender et al (1951)</td>
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<tr>
<td>B/r</td>
<td>Saline-Pi</td>
<td>0.34</td>
<td>-</td>
<td>X-ray</td>
<td>Hollaender et al (1951)</td>
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<tr>
<td>E. coli O157 (non-verotoxin type)</td>
<td>Saline solution (10^{-2} concentration) anaerobic cond.</td>
<td>0.5</td>
<td>-20</td>
<td>Gamma</td>
<td>Niyahara and Niyahara (2002)</td>
</tr>
<tr>
<td>E. coli O157 (non-verotoxin type)</td>
<td>Saline solution (10^{-2} concentration) anaerobic cond.</td>
<td>0.48</td>
<td>-20</td>
<td>E-beam</td>
<td>Niyahara and Niyahara (2002)</td>
</tr>
<tr>
<td>E. coli O157 (non-verotoxin type)</td>
<td>Saline solution (10^{-2} concentration) stored at 4°C before treatment, anaerobic cond.</td>
<td>0.22</td>
<td>-20</td>
<td>Gamma</td>
<td>Niyahara and Niyahara (2002)</td>
</tr>
</tbody>
</table>